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hereby certify that annexed is a true copy of the Provisional specification in
connection with Application No. PP 9960 for a patent by SILVERBROOK
RESEARCH PTY LTD filed on 23 April 1999.

WITNESS my hand this
Second day of November 1999

KAY WARD
TEAM LEADER EXAMINATION
SUPPORT AND SALES



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PRIORITY DOCUMENT**

AUSTRALIA
Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant(s) :

SILVERBROOK RESEARCH PTY LTD

Invention Title:

A METHOD AND APPARATUS (SPRINT01)

The invention is described in the following statement:

AN IMAGE CREATION METHOD AND APPARATUS (SPRINT01)

Field of the Invention

The present invention relates to the field of printing and, in particular, discloses a double sided ink-jet printing system having page width print heads.

Background of the Invention

Many different types of printers are generally known. For example, offset printers, ink-jet prints, laser printers, etc., are utilised to provide for output printing on output media.

With any printer device, it is desirable to provide for as inexpensive a form of printing as possible. Also, it is often desirable to have an extremely compact arrangement in addition to printing on both sides of an output print media such as paper sheets.

Summary of the Invention

It is an object of the present invention to provide an improved compact double sided ink jet printing system.

In accordance with a first aspect of the present invention, there is provided a dual sided printing system comprising: two imaging engines one for printing on each side of a portion of print media, each of the imaging engines comprising: at least two ink jetting printhead units having fault tolerant properties, the printhead units, in combination, providing for pagewidth printing of images on the print media.

Each of the imaging engines further can comprise: a transfer roller and wherein the ink jetting print head units jet ink onto the transfer roller which in turn carries the ink to the print media.

Each of the imaging engines further can comprise a drying unit for drying ink once transposed to the printing media. The drying unit can comprise an infra-red tube.

The printhead units can include a pagewidth printhead. The pagewidth printhead preferably can include a

printhead ink supply along a back surface thereof and further comprising: a series of detachable ink cartridges each including an ink supply chamber which upon attachment to the printhead, the ink supply chamber can be in contact with the printhead ink supply. The printhead can comprise a full color printhead.

The detachable ink cartridges are preferably mounted on a top surface of the printing system. The number of ink cartridges can be at least four and the ink cartridges are preferably abutted one next to another.

Description Preferred in Other Embodiments

The preferred embodiment of the present invention is as set out in the attached appendix B which provides for a detailed description of the implementation of a printer system denoted SPRINT, including the adaptation to a two side printer system utilising a page width ink-jet print head.

The ink jet technology utilized can be a wide pagewidth printing system as disclosed in the attached appendix A.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments in the attached documentation without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

We Claim:

1. A dual sided printing system comprising:
two imaging engines one for printing on each side
5 of a portion of print media, each of said imaging engines
comprising:
at least two ink jetting printhead units having
fault tolerant properties, said printhead units, in
combination, providing for pagewidth printing of images on
10 said print media.
2. A system as claimed in claim 1 wherein each
of said imaging engines further comprise:
a transfer roller and wherein said ink jetting
15 print head units jet ink onto said transfer roller which in
turn carries the ink to said print media.
3. A system as claimed in any previous claim
wherein each of said imaging engines further comprises a
drying unit for drying ink once transposed to said printing
20 media.
4. A system as claimed in claim 3 wherein said
drying unit comprises an infra-red tube.
5. A system as claimed in any previous claim
wherein said printhead units include a pagewidth printhead.
25
6. A system as claimed in claim 5 wherein said
pagewidth printhead includes a printhead ink supply along a
back surface thereof and further comprising:
a series of detachable ink cartridges each
30 including an ink supply chamber which upon attachment to
said printhead, said ink supply chamber is in contact with
said printhead ink supply.
7. A system as claimed in any previous claim
wherein said printhead comprises a full color printhead.
- 35 8. A system as claimed in claim 6 wherein said
detachable ink cartridges are mounted on a top surface of
said printing system.

9. A system as claimed in claim 8 wherein the number of ink cartridges is at least four and said ink cartridges are abutted one next to another.

10. A printing system substantially as
5 hereinbefore described with reference to the accompanying appendicies.

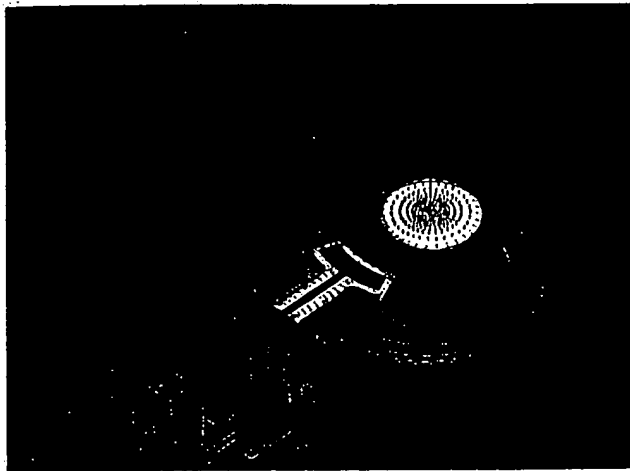
ABSTRACT

A dual sided printing system comprising: two imaging
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onto the transfer roller which in turn carries the ink to
the print media. Each of the imaging engines further can
comprise a drying unit for drying ink once transposed to
the printing media

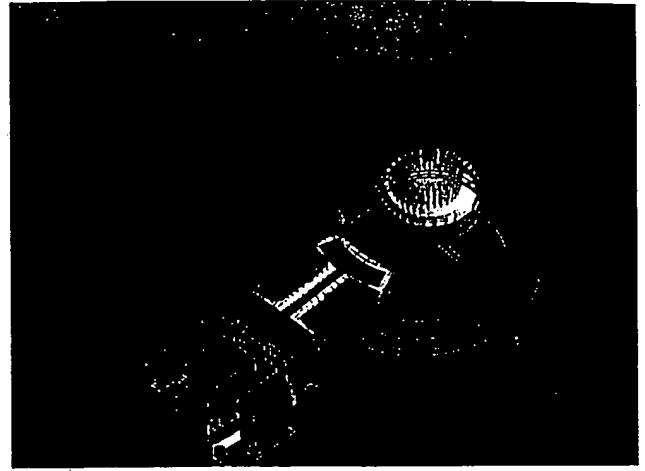
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MEMJET

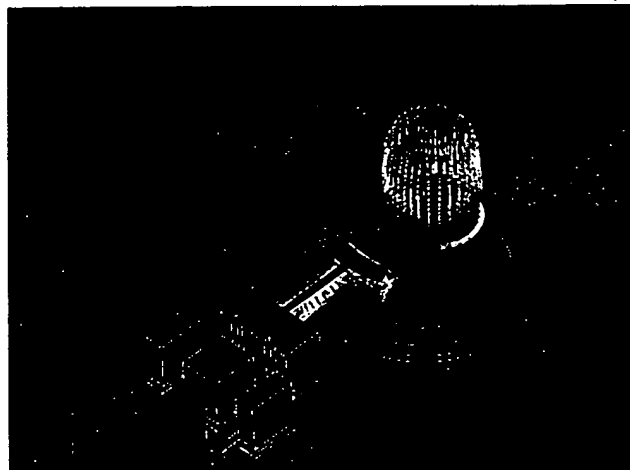
Micro Electro Mechanical Inkjet



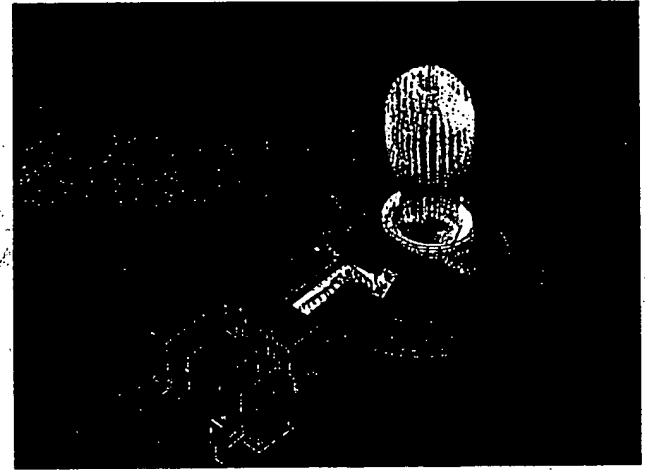
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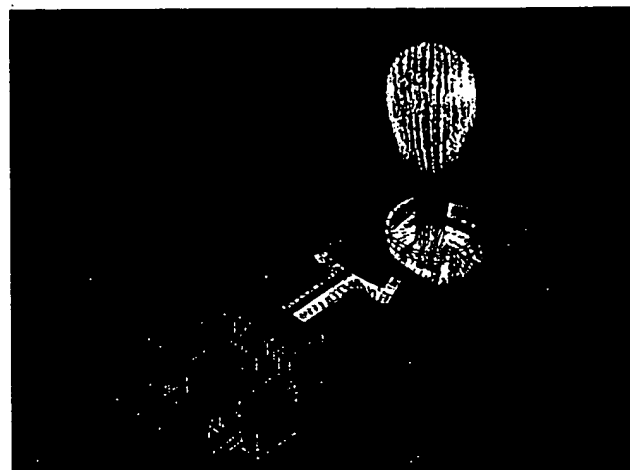
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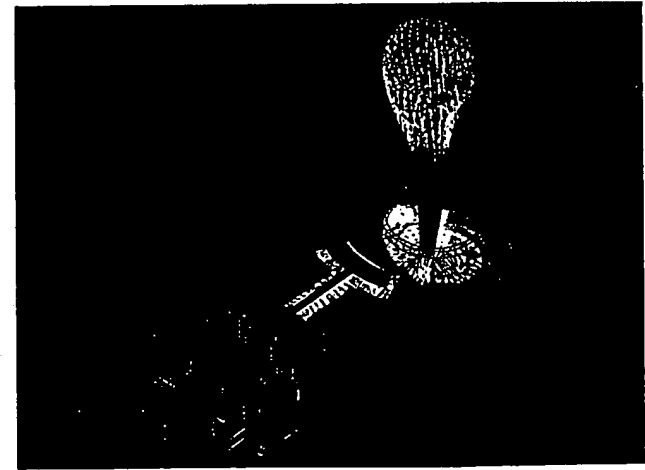
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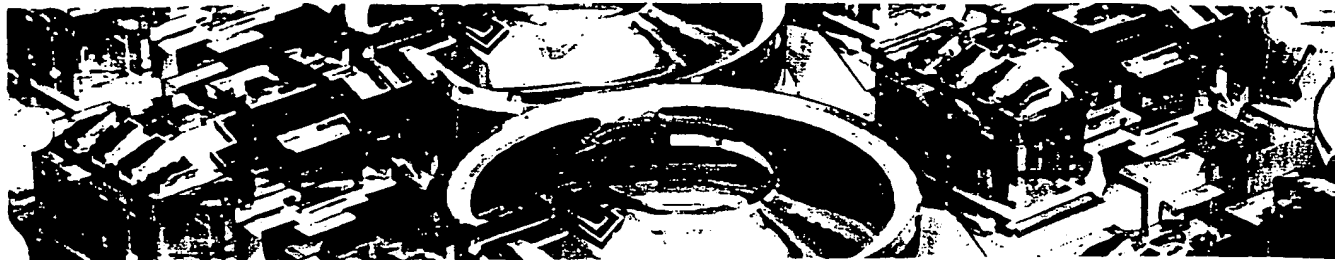
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MEMJET INTRODUCTION

Memjet is a new digital printing technology under development at Silverbrook Research. It is a 'clean slate' development aimed at developing the 'perfect' print technology for a wide range of applications for which current digital printing technologies are inadequate. The price/performance advantage over existing technologies such as laser printers and thermal inkjet printers is around two orders of magnitude.

Key Features of Memjet:

- Pagewidth inkjet printing - no scanning printheads, therefore very fast.
- High nozzle count: 51,200 nozzles for A4/letter.
- Full quality color photographic images at 1600 dpi.
- Full quality text, including Japanese Kanji.
- Wide ink and paper flexibility - three times less water than 600 dpi printers.
- High speed - 30 pages per minute (ppm) to 4000 ppm.
- High nozzle density - 25,600 nozzles in a 75mm² chip (compare to latest HP - 300 nozzles in 75 mm²).
- Low cost - under \$10 for a 30 ppm letter/A4 full color 1600 dpi printhead.
- Low power allows battery operation for many applications.
- Small size - printers incorporated in mobile phones, cameras, even pens.
- Simple drive circuits - 3V digital ASIC with low pincount.
- High volume manufacture - 56 million 8" heads from a 25,000 wafer per month fab.
- Low manufacturing investment - can adapt a 0.5 micron CMOS fab.
- Excellent patent protection - 220 US patents pending, both basic patents and strategic blocking patents.

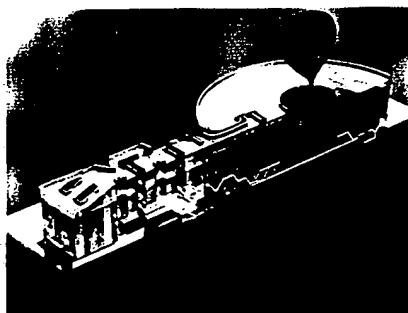
Radical, not Evolutionary

The closest technology to Memjet is Thermal Ink Jet (TIJ). This technology was invented roughly simultaneously by Canon and Hewlett-Packard around 1980 (Canon's variety is known as 'Bubblejet'), and currently results in annual revenues around \$24 billion.

Thermal inkjet printheads propel a droplet of ink out of a nozzle by superheating a tiny volume of ink. This ink undergoes a flash evaporation process, forming a bubble which pushes the ink out of the nozzle.

There has been a massive investment in developing thermal inkjet technology, which has steadily advanced products from initial 200 dpi black only printers with 12 nozzles, to current full color 600 dpi printers containing printheads with as many as 608 nozzles.

However, Memjet does not use the thermal inkjet operating principle, and is not an extension of TIJ technology.



Cross section of a Memjet nozzle

Micro Electro Mechanical Systems (MEMS)

Memjet is derived from MEMS technology. MEMS is Micro Electro Mechanical Systems, and is basically the construction of mechanical systems using VLSI chip fabrication techniques. MEMS allows the integration of hundreds of millions of mechanical devices on a wafer. Certain MEMS processes (such as the Memjet process) allow the integration of MEMS and CMOS processing. This is essential for a pagewidth printhead, otherwise around 50,000 off-chip connections would be required, making the cost prohibitive for volume markets.

MEMS devices are used in many applications, though few of these applications have reached substantial volume sales. Some of the best known are

CONTENTS

Memjet Introduction	3
Advantages	6
Yield	13
Volume	15
Prototype Fabrication	17



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accelerometers for car airbags, and Texas Instruments' DMD (Digital Micromirror Device).

The DMD is an array of around 1 million tiny mirrors on a CMOS chip. Each mirror is independently deflected in response to video image data distributed on the CMOS chip. Each mirror reflects light either towards a viewing screen, or towards a baffle. As all of the mirrors are independently controlled, a large amount of data can be projected even though the individual speed of the mirrors is only around 50 kHz.

Memjet is conceptually similar. A Memjet printhead contains around 25,000 tiny paddles on a CMOS chip. Each paddle is independently deflected in response to page image data distributed on the CMOS chip. When deflected, each paddle pushes a microscopic ink drop out of a nozzle towards the paper. As all of the paddles are independently controlled, a large amount of data can be printed even though the individual speed of the paddles is only around 40 kHz.

Memjet Value Proposition

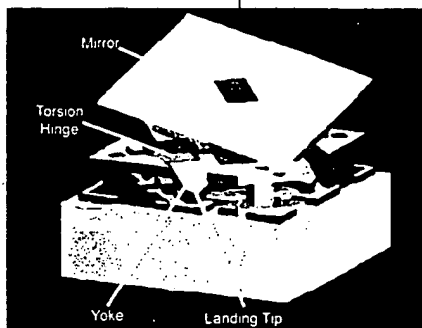
The value proposition of Memjet is 'practical pagewidth inkjet printing'.

A scanning printhead is fundamentally around 100 times slower than a pagewidth printhead. This is because the a scanning printhead must scan across the page numerous times - around 40

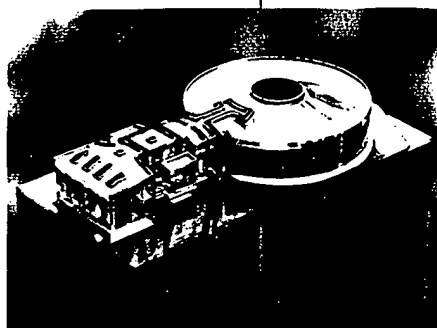
times for draft mode and 200 times for photo quality.

The most fundamental difference between scanning and pagewidth printheads is the width of the printhead.

There is an essential divide between scanning printheads (roughly 1/2") and pagewidth printheads (8" for US letter/A4). Printheads between these values are not very useful - there is no 'evolutionary' progression.



Texas Instruments
Digital Micromirror Device



Memjet
Inkjet nozzle

For example: you can't make a letter/A4 pagewidth printer out of a single 4" printhead. Neither can you make a reasonable scanning printer - a 4" print swath is virtually impossible to 'stitch' on the paper without getting highly objectionable lines across the page.

A pagewidth printhead means lots of nozzles. For a 1600 dpi, 4 color, 8" printhead, 51,200 nozzles are required. This compares to typically 300 nozzles for TIJ, and 128 nozzles for piezoelectric inkjets (such as Epson and Tektronix).

Previous pagewidth printhead projects

Pagewidth printheads have long been the 'holy grail' of the inkjet industry, and have been the subject of intensive research at various large companies for more than a decade.

Previous attempts at pagewidth inkjets have mostly tried to scale up either of the two current technologies - thermal inkjet or piezoelectric inkjet. Both of these approaches fail for a number of fundamental reasons.

Why cant you make pagewidth thermal inkjet printheads?

Thermal inkjet (TIJ or Bubblejet - HP and Canon's technology) is not suitable for pagewidth printheads as the power consumption is around 100 times too high. This makes it

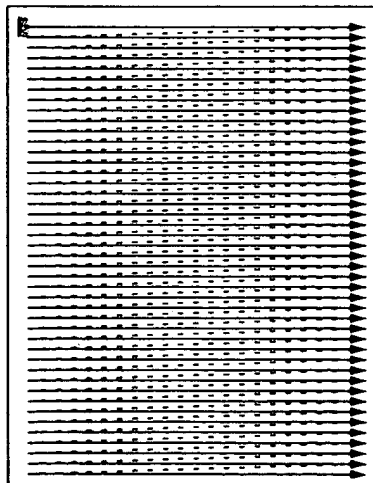
very difficult to get sufficient power into the printhead. However, even more difficult is getting the waste heat out of the printhead without boiling the ink.

TIJ cannot be made in a monolithic process, as the nozzle plates must be around 30 microns thick to withstand the transient pressures generated by the bubble. As a result, there are extraordinary manufacturing difficulties in scaling up from small printheads to pagewidth printheads. These include differential thermal expansion (making it extremely difficult to align the nozzles at both ends of a long printhead simultaneously) and cracking of the silicon chips due to the high stresses during nozzle plate attachment.

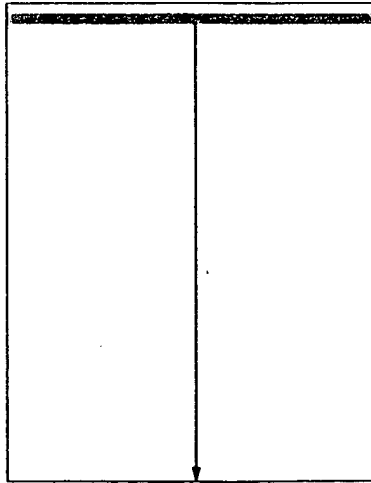
Also, TIJ and Bubblejet printheads wear out due to kogation and cavitation (neither of these problems affect Memjet or piezoelectric printheads). While it is cost effective to frequently replace 1 cm long scanning printheads, pagewidth printheads should have a longer lifetime.

Why cant you make pagewidth piezoelectric inkjet printheads?

The problems with scaling piezoelectric printheads are entirely different than those for TIJ. The main problem is acoustic crosstalk. As the printhead length increases, the delay between the acoustic pulse of a piezo actuator and its acoustic reflections from the ends of the printhead increase. This causes the pulse to interfere with itself on a timescale which reaches into the critical time of



Scanning printhead



Pagewidth printhead

drop ejection. Also, as the number of nozzles increases, the number of possible interference combinations undergoes a combinatorial explosion. This makes it essentially impossible to obtain consistent drop ejection at various places on the printhead.

Another problem is cost. Silicon is not a piezoelectric material, and it is extremely difficult to integrate piezoelectric materials on CMOS chips. This means that a separate external connection is required for each nozzle. A printhead equivalent to an 8" Memjet printhead would require at least 51,201 external connections. While theoretically possible, the cost of these connections is exorbitant.

The drive voltage required is around 100 V to 200 V, so it is also difficult to integrate large numbers of drivers on a single chip.

Another problem preventing integration is that the piezoelectric material must be electrically poled at around 100,000 Volts, which makes it extremely difficult to protect integrated CMOS circuitry.

How fast can a Memjet printer go?

For most consumer and PC printer applications, the full speed of Memjet is not required. In these applications, the print speed will generally be limited by the low cost paper movement mechanism.

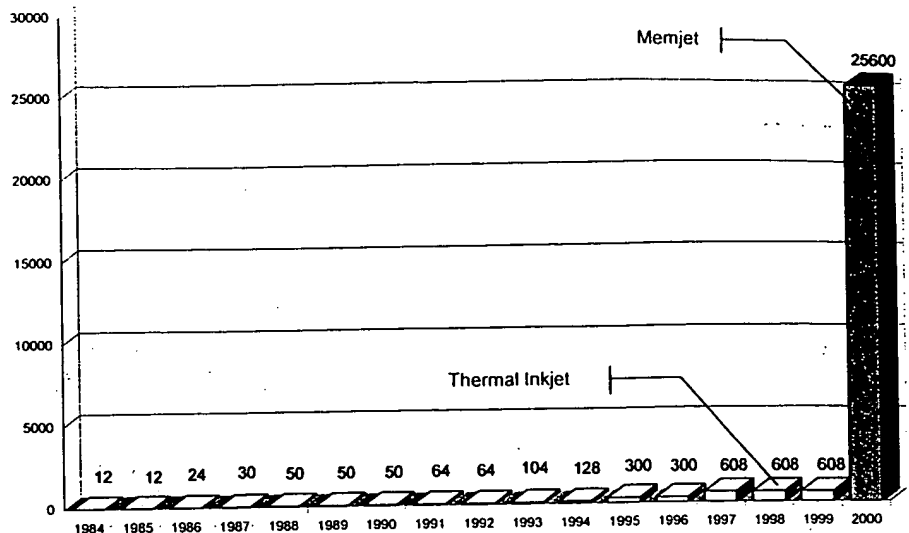
However, for various industrial and commercial printing applications, higher print speeds are desirable.

Individual Memjet nozzles can operate at 40 kHz (and are likely to operate up to 100 kHz). At 1600 dpi, this means a print speed of 25 inches per second. A 'standard' Memjet printhead has four channels for four ink colors. If this printhead is used to print a single color instead, then the maximum print speed is 100 inches per second. A 34 inch wide web (paper roll) fed printer, with printheads on both sides of the paper, printing at 100 inches per second, has an equivalent print speed of 4,364 ppm. At these print speeds, it is possible to compete directly with commercial offset printing.

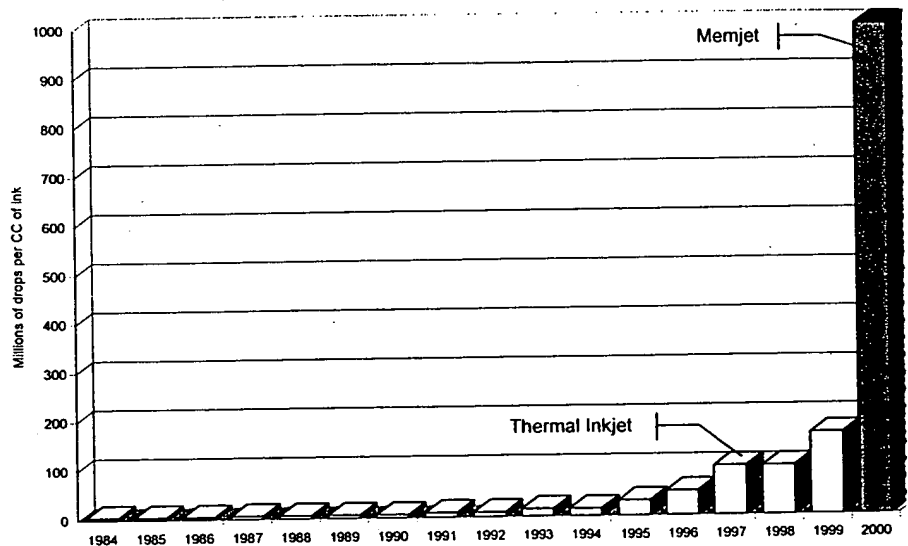
Memjet - TIJ trends

The bar charts to the right show the trends for thermal inkjet printheads from the first commercial products to the present. These trends are compared to what is expected to be the first Memjet printhead - a 4", 4 color, 1600 dpi printhead with 25,600 nozzles. Two such printhead chips butted together make up an 8" pagewidth printhead.

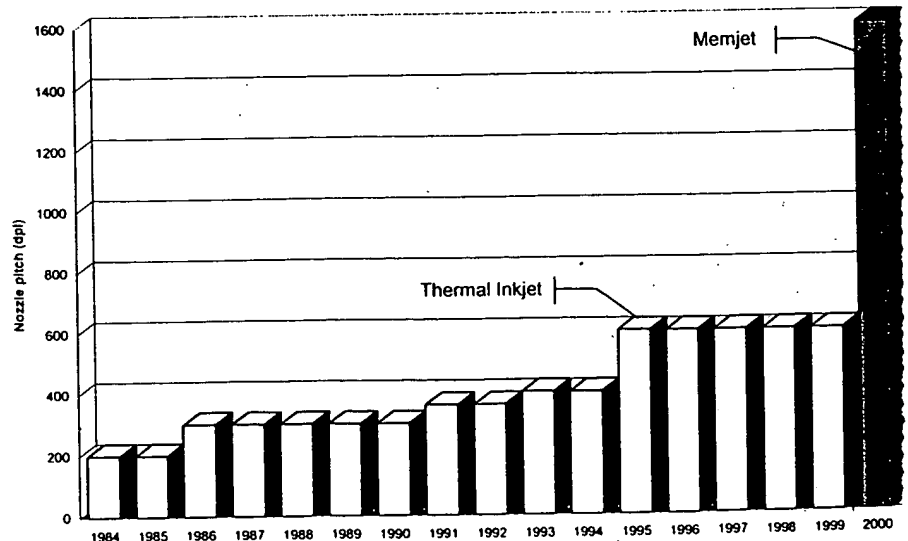
Nozzles per monolithic printhead



Ink drops per CC



Nozzle pitch



ADVANTAGES

The list of advantages is long, and there are no disadvantages listed. This is because Silverbrook Research has spent years analyzing the problems with previous technologies, and ensuring that these problems are solved for Memjet. Memjet has been through 47 major design iterations to converge on its current state, where we believe that further improvements will not be significant. This quest for perfection is ongoing, and it is our intention to correct any undiscovered problems as quickly as possible. As is well known, a problem detected at an early stage can be orders of magnitude cheaper to correct than a problem detected at a prototype or production stage.

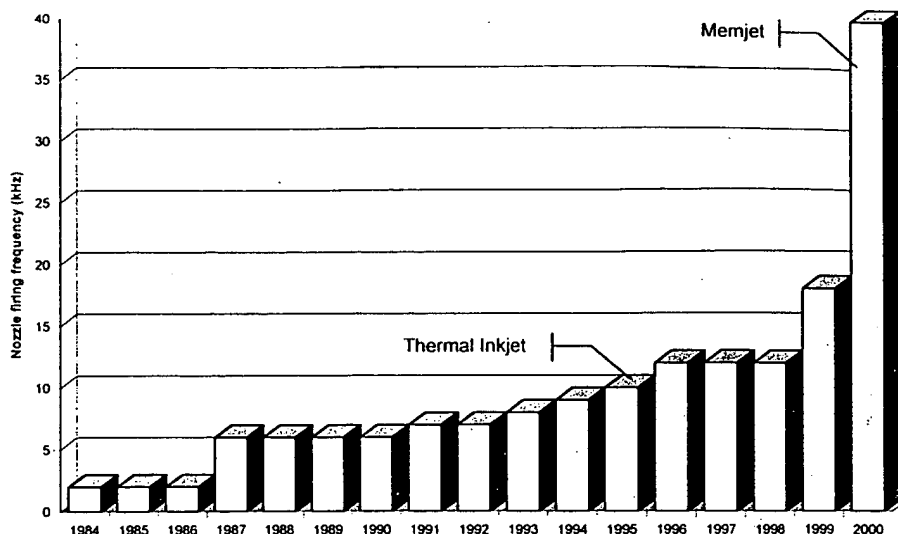
High Resolution

The true resolution of Memjet is 1600 dots per inch (dpi) in both directions. This allows full photographic quality color images, and high quality text (including Kanji). Higher resolutions are possible with the technology. 2400 dpi and 4800 dpi versions have been investigated for special applications, but 1600 dpi is chosen as ideal for most applications. The true resolution of commercially available advanced thermal inkjet devices is around 600 dpi. For piezoelectric systems such as those from Epson the true resolution is substantially lower, but the printhead makes many overlapping passes over each point giving an 'effective resolution' of 1440 dpi, at the expense of speed. 'Addressable resolution' is now often quoted in advertising to give the illusion of higher resolution.

Excellent Image Quality

High image quality requires high resolution and accurate placement of drops. The monolithic pagewidth nature of Memjet allows drop placement to sub-micron precision. High accuracy is also achieved by eliminating misdirected drops, electrostatic deflection, air turbulence, and eddies, and maintaining highly consistent drop volume and velocity. Image quality is also ensured by the provision of sufficient resolution to avoid requiring multiple ink densities. Five color or 6 color 'photo' inkjet systems introduce halftoning artifacts in mid tones (such as flesh tones) if the dye interaction and drop sizes are not absolutely perfect. This problem is eliminated in bi-level three color systems such as Memjet.

Nozzle firing frequency

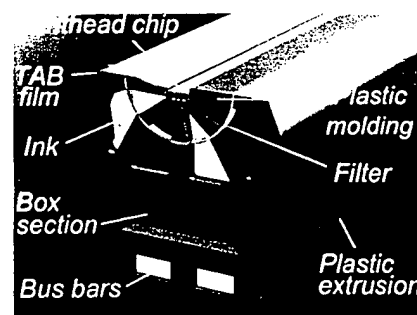


High Speed - up to 120 ppm per printhead

The pagewidth nature of the printhead allows high-speed operation, as no scanning is required. The print speed of a Memjet based printer will usually be determined by market requirements and the paper handling mechanisms required. For most consumer or SOHO applications, 30 ppm printing is around the optimum, as faster printers are dominated by complex and expensive paper handling. To achieve 30 ppm, the Memjet printhead is operated at a drop repetition rate of 10 kHz. The maximum drop repetition rate for Memjet is 40 kHz, allowing 120 ppm full color printing from a single printhead.

Low Cost

A photo-width photographic printhead assembly is projected to cost under \$5, and a pagewidth A4 printhead assembly (using two 4" printhead equivalents) is projected to cost less than \$10 when manufactured using a 0.5 micron CMOS process on 8" wafers.



When early 300 mm fabs eventually become cost effective, monolithic 8" printheads can be fabricated on a single

wafer, reducing production costs further.

All Digital Operation

The high resolution of the printhead is chosen to allow fully digital operation using digital halftoning. This eliminates color non-linearity (a problem with continuous tone printers), and simplifies the design of drive ASICs.

Small Drop Volume

To achieve true 1,600 dpi resolution, a small drop volume is required. Memjet's drop volume is one picoliter (1 pl). The drop size of advanced commercial piezoelectric and thermal inkjet devices is around 10 to 30 pl. This has been steadily reduced over the previous two decades from original drop volumes of around 100 pl. A small drop volume also allows substantially less ink carrier (typically water) to be printed to the page, allowing much faster drying and eliminating print-through. It is theoretically possible to build a 1600 dpi thermal inkjet printhead with 1 pl drops. However, such a printhead would need to print 7.11 times as many drops as a current 600 dpi printer. It would be 7 times slower, and use around 4 times the energy, as a 600 dpi printhead with an equivalent number of nozzles. Thermal inkjet printers are already too slow and use too much power, so it is unlikely that such print-heads will be built. Memjet uses around 100 times less energy to print a drop, and uses around 100 times as many nozzles (51,200 versus around 512 for thermal inkjet), so there are no speed or power problems arising from the high resolution.

Accurate Control of Drop Velocity

As the drop ejector is a precise mechanical mechanism, and does not rely on bubble nucleation, accurate drop velocity control is available. This allows low drop velocities (4 m/s) to be used in applications where media and airflow can be controlled. Drop velocity can be accurately varied over a considerable range by varying the energy provided to the actuator. High drop velocities (10 to 15 m/s) suitable for printing on rough or fibrous surfaces (such as 'plain paper') can be achieved using variations of the nozzle chamber and actuator dimensions. Twelve meters per second is chosen as the nominal velocity for Memjet plain paper applications where airflow is uncontrolled.

Fast Drying

A combination of very high resolution, very small drops, and high dye density allows full color printing with much less water ejected. Memjet ejects around one third of the water of a 600 dpi thermal inkjet printer. This allows fast drying and virtually eliminates paper cockle.

Wide Temperature Range

Memjet is designed to cancel the effect of ambient temperature. Only the change in ink characteristics with temperature affects operation and this can be electronically compensated. Operating temperature range is expected to be 0 °C to 50 °C for water based inks.

No Special Manufacturing Equipment Required

The manufacturing process for Memjet leverages entirely from the established semiconductor manufacturing industry. Most inkjet systems encounter major difficulty and expense in moving from the laboratory to production, as high accuracy specialized manufacturing equipment is required. For Memjet, the equipment required has already been developed at a cost of many billions of dollars for the semiconductor industry.

High Production Capacity Available

An 8" CMOS fab with 25,000 wafer starts per month can produce around 56 million 8" printheads per annum. There are currently many such CMOS fabs in the world.

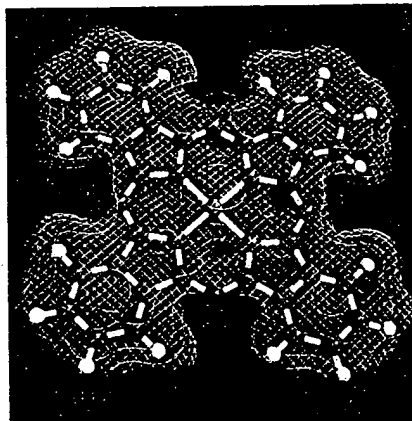
Low Factory Setup Cost

The factory set-up cost is low because existing 0.5 micron 6" and 8" CMOS fabs can be used. At the time of

projected introduction of the printheads these fabs should be fully amortized, and essentially obsolete for CMOS logic production. Therefore, volume production can use 'old' existing facilities. Most of the MEMS post-processing can also be performed in a CMOS fab, but at least one new piece of equipment will be required, - a deep silicon etcher using the 'Bosch process'. These machines are available from Alcatel, PlasmaTherm, and Surface Technology Systems.

Good Light-Fastness

As the ink is not heated, there are few restrictions on the types of dyes that can be used. This allows dyes to be chosen for optimum light-fastness. Some recently developed dyes from companies such as Zeneca Specialties and BASF have light-fastness of 7 on the blue wool scale. This is equal to the light-fastness of many pigments, and considerably in excess of photographic dyes and of early inkjet dyes.



Copper phthalocyanine - a blue chromophore - showing an electron density isosurface mapped with electric potential

Good Water-Fastness

As with light-fastness, the lack of thermal restrictions on the dye allows selection of dyes for characteristics such as water-fastness. For extremely high water-fastness (as is required for washable fabrics) reactive dyes can be used.

Excellent Color Gamut

The use of transparent dyes of high color purity allows a color gamut considerably wider than that of offset printing and silver halide photography. Offset printing in particular has a restricted gamut due to light scattering from the pigments used. With three-color systems (CMY) or four-color systems (CMYK) the gamut is necessarily limited to the tetrahedral volume between the color vertices. Therefore it

is important that the cyan, magenta and yellow dyes are as spectrally pure as possible. A slightly wider 'hexcone' gamut that includes pure reds, greens, and blues can be achieved using a 6 color (CMYRGB) model. Such a six-color printhead can be made economically with a width of only 1 mm.

Elimination of Color Bleed

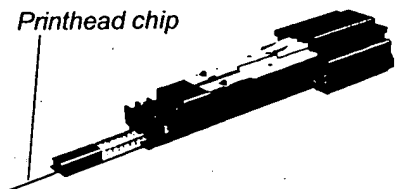
Ink bleed between colors occurs if the different primary colors are printed while the previous color is wet. While image blurring due to ink bleed is typically insignificant at 1600 dpi, ink bleed can 'muddy' the midtones of an image. Ink bleed can be eliminated by using microemulsion-based ink, for which Memjet is highly suited. The use of microemulsion ink can also help prevent nozzle clogging and ensure long-term ink stability.

Advanced Ink Formulations

Silverbrook Research has world-class expertise in quantum chemistry (refer to papers in J. Phys. Chem. and Chemical Physics Letters), and is applying this to the development of a new class of inks with advanced properties.

High Nozzle Count

Memjet has 19,200 nozzles in a monolithic CMY three-color photographic printhead. While this is large compared to other printheads, it is a small number compared to the number of devices routinely integrated on CMOS VLSI chips in high volume production. It is also less than 3% of the number of movable mirrors which Texas Instruments integrates in its Digital Micromirror Device (DMD), manufactured using similar CMOS + MEMS processes.



Cutaway of packaged photographic printhead

51,200 Nozzles per A4 Pagemwidth Printhead

A four-color (CMYK) Memjet printhead for pagemwidth letter/A4 printing uses two chips. Each 0.65 cm² chip has 25,600 nozzles for a total of 51,200 nozzles.

Integration of Drive Circuits

In a printhead with as many as 200 nozzles, it is essential to integrate data distribution circuits (shift registers), data timing, and drive transistors with the nozzles. Otherwise, a minimum of 51,201 external connections would be required. This is a severe problem with piezoelectric inkjets, as drive circuits cannot be integrated on piezoelectric substrates. Integration of many millions of connections is common in CMOS VLSI chips, which are fabricated in high volume at high yield. It is the number of off-chip connections that must be limited.

Monolithic Fabrication

Memjet is made as a single monolithic CMOS chip, so no precision assembly is required. All fabrication is performed using standard CMOS VLSI and MEMS processes and materials.

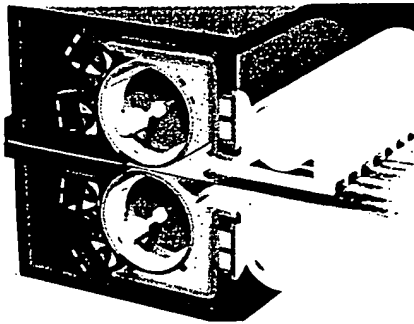
In thermal inkjet and some piezoelectric inkjet systems, the assembly of nozzle plates with the printhead chip is a major cause of low yields, limited resolution, and limited size. Also, pagewidth arrays are typically constructed from multiple smaller chips. The assembly and alignment of these chips is an expensive process.

Modular, Extendable for Wide Print Widths

Long pagewidth printheads can be constructed by butting 'standard' 100 mm Memjet heads together. The edge of the Memjet printhead chip is designed to automatically align to adjacent chips. One printhead gives a photographic size printer, two gives an A4 printer, and four gives an A3 printer. Larger numbers can be used for high speed digital printing, pagewidth wide format printing, and fabric printing.

Low Cost Simultaneous Double Sided Printing

Double sided printing (known as 'duplex' in the office market, and 'perfect' in the commercial print market) can be implemented at low cost simply by including an extra printhead on the other side of the paper, and duplicating the appropriate logic and image processing circuits. The cost and complexity of providing two printheads is less than that of mechanical systems to turn over the sheet of paper.



Simultaneous duplex printhead assembly

Straight Paper Path

As there are no drums required, a straight paper path can be used to reduce the possibility of paper jams. This is especially relevant for office duplex printers, where the complex mechanisms required to turn over the pages are a major source of paper jams.

High Efficiency

Thermal inkjet printheads are only around 0.1% efficient (electrical energy input compared to drop kinetic energy and increased surface energy). Memjet is more than 10 times as efficient.

Self-Cooling Operation

The energy required to eject each drop is 142 nJ (0.142 microJoules), a small fraction of that required for thermal inkjet printers. The low energy allows the printhead to be completely cooled by the ejected ink, with only a 32 °C worst-case ink temperature rise. No heat sinking is required.

Low Pressure

The maximum pressure generated in a Memjet printhead is around 60 kPa (0.6 atmospheres). The pressures generated by bubble nucleation and collapse in thermal inkjet and bubblejet systems are typically in excess of 10 MPa (100 atmospheres), which is 160 times the maximum Memjet pressure. The high pressures in bubblejet and thermal inkjet designs result in high mechanical stresses.

Low Power

A 30 ppm A4 Memjet printhead requires a maximum of 67 Watts when printing full 3-color black. When printing 5% coverage, average power consumption is only 3.4 Watts.

Low Voltage Operation

Memjet can operate from a single 3V supply, the same as typical drive ASICs. Thermal inkjets typically require at least 20 V, and piezoelectric inkjets often require more than 50 V. The Memjet actuator is designed for nominal operation at 2.8 volts, allowing a 0.2 V drop across the drive transistor, to achieve 3V chip operation.

Operation from 2 or 4 AA Batteries

Power consumption is low enough that a photographic Memjet printhead can operate from AA batteries. A typical 6 x 4 inch photograph requires less than 20 Joules to print (including drive transistor losses). Four AA batteries are recommended if the photo is to be printed in 2 seconds. If the print time is increased to 4 seconds, 2 AA batteries can be used.

Battery Voltage Compensation

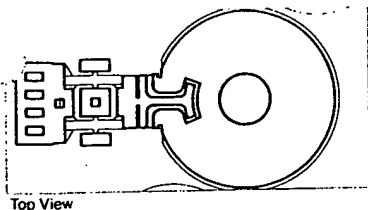
Memjet can operate from an unregulated battery supply, to eliminate efficiency losses of a voltage regulator. This means that consistent performance must be achieved over a considerable range of supply voltages. Memjet senses the supply voltage, and adjusts actuator operation to achieve consistent drop volume.

Advanced Nozzle Clearing

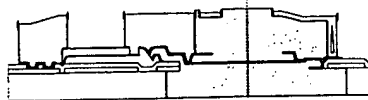
Memjet employs two novel patented techniques to clear clogged nozzles, and most conventional techniques can also be used. The degree of potential nozzle clogging is highly dependent on the ink formulation, which depends on the application. In photographic applications clog-proof inks can be used. Hot melt inks can also be completely clog free. When using aqueous inks, it is essential to use nozzle capping and to include a humectant in the ink.

Small Actuator and Nozzle Area

The area required by a Memjet nozzle, actuator, and drive circuit is 3200 μm^2 . This is much less than 1% of the area required by piezoelectric inkjet nozzles, and around 1.5% of the area required by TIJ nozzles. The actuator area directly affects the printhead manufacturing cost.

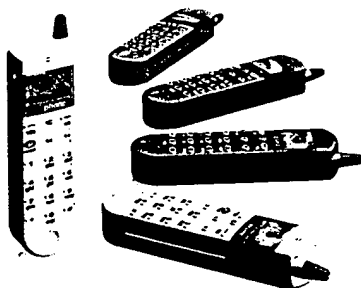


Top View



Small Total Printhead Size

An entire printhead assembly (including ink supply channels) for a letter/A4, 30 ppm, 1600 dpi, four color printhead is 210 x 12 x 10 mm. The small size allows incorporation into notebook computers and miniature printers. A photograph printer is 106 x 8 x 8 mm, allowing inclusion in pocket digital cameras, palmtop PCs, mobile phone/fax, and so on. Ink supply channels take most of this volume. The photographic printhead chip itself is only 102 x 0.55 x 0.3 mm.



Printers in 3G mobile phones

Various Nozzle Capping Systems

Nozzle capping systems have been designed for various applications.

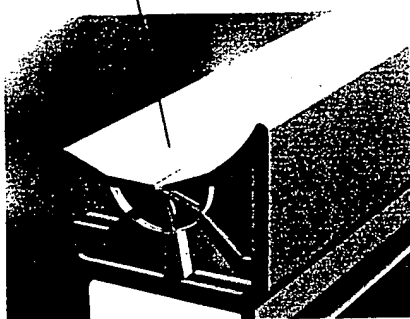
A miniature nozzle capping system has been designed for portable and photographic applications. For a photographic printer this nozzle capping system is only 106 x 5 x 4 mm, and does not require the printhead to move.

For very low cost printers, such as printers incorporated into pens, the nozzle capping mechanism is a single piece of molded plastic costing less than a cent.

In desktop printers, the printhead can be capped against a transfer roller for

robust operation and consumer-proofing.

Elastomeric seal caps printhead against the transfer roller



Cross section of packaged printhead (CEprint version)

High Manufacturing Yield

The projected manufacturing yield (at maturity) of the Memjet printheads is at least 80%, as it is primarily a 0.5 micron digital CMOS chip with an area of only 0.15 cm² per inch of printhead. Most modern CMOS processes achieve high yield with chip areas in excess of 1 cm². For chips less than around 1 cm², cost is roughly proportional to chip area. Cost increases rapidly between 1 cm² and 4 cm², with chips larger than this rarely being practical. There is a strong incentive to ensure that the chip area is less than 1 cm².

For thermal inkjet and bubblejet printheads, the chip width is typically around 5 mm, limiting the cost effective chip length to 1 to 2 cm. A major target of Memjet has been to reduce the chip width as much as possible, allowing cost effective monolithic pagewidth printheads.

In the early stages of manufacture, before high yields are obtained, fault tolerance can be used. Although fault tolerance doubles the 'raw' chip area, wafers with defect densities as high as 100 defects per cm² can still obtain good printhead yields.

Low Process Complexity

With digital IC manufacture, the mask complexity of the device has little or no effect on the manufacturing cost or difficulty. Cost is proportional to the number of process steps, and the lithographic critical dimensions. Memjet uses a standard 0.5 micron 1P2M CMOS manufacturing process, with an additional 7 MEMS mask steps. This makes the manufacturing process less complex than a typical 0.25 micron CMOS logic process with 5 level metal. However, as the MEMS postprocessing

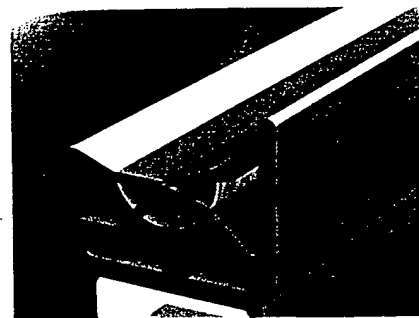
is not standard, a significant amount of process development is required. Considerable effort has been undertaken to minimize the complexity and risk of this process development. However, since any process development is usually difficult and expensive, this is likely to be the highest portion of the remaining development costs.

Simple Testing

Memjet includes test circuits and a test strategy that allows most testing to be completed at the wafer probe stage. Testing of all electrical properties, including the resistance of the actuator, can be completed at this stage. However, actuator motion can only be tested after release from the sacrificial materials. Actuators can be tested before being filled with ink using optical methods. The paddle is reflective and the nozzle chamber is transparent. Paddle deflection can be measured accurately by counting interference fringes of monochromatic light. Final testing of packaged printheads is readily performed by printing a test pattern which is automatically checked using a linear image sensor.

Low Cost Packaging

Memjet is packaged in an injection molded polycarbonate package. All connections are made using Tape Automated Bonding (TAB) technology, though wire bonding can be used as an option. All connections are along one edge of the chip.



Molded plastic package

Relaxed Critical Dimensions

The critical dimension (CD) of the Memjet CMOS drive circuitry is 0.5 microns. Advanced digital ICs such as microprocessors currently use CDs of around 0.25 microns, which is two device generations more advanced than the Memjet printhead requires. Most of the MEMS post processing steps have CDs of 1 micron or greater.

Low Stress during Manufacture

Devices cracking during manufacture are a critical problem with both thermal inkjet and piezoelectric devices. This limits the size of the printhead that it is possible to manufacture. The stresses involved in the manufacture of Memjet printheads are no greater than those required for CMOS fabrication. Memjet printheads are not sawn from the wafer, but are gently plasma etched instead.

No Scan Banding

Memjet is a full pagewidth printhead, so does not scan. This eliminates one of the most significant image quality problems of inkjet printers. Banding due to other causes (mis-directed drops, printhead misalignment) is usually a significant problem in pagewidth printheads. These causes of banding have also been addressed.

'Perfect' Nozzle Alignment

All of the nozzles within a printhead are aligned to sub-micron accuracy by the 0.5 micron stepper used for the lithography of the printhead. Nozzle alignment of two 4" printheads to make an A4 pagewidth printhead is achieved with the aid of mechanical alignment features on the printhead chips. This allows automated mechanical alignment (by simply pushing two printhead chips together) to within 1 micron. If finer alignment is required in specialized applications, 4" printheads can be aligned optically.

Controllable Drop Velocity

An accurately controlled drop velocity improves image quality, as the position of dots on the moving substrate is more accurate. An accurate drop velocity also enables a lower nominal drop velocity, which reduces power consumption. A low drop velocity requires laminar airflow, with no eddies, to achieve good drop placement on the print medium. This is achieved by the design of the printhead packaging.

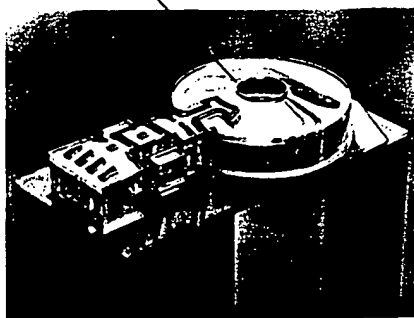
For printing on 'rough' surfaces higher drop velocities are desirable. Drop velocities up to 15 m/s can be achieved using variations of the design dimensions. It is possible to manufacture printheads with a 4 m/s drop velocity, and printheads with a 15 m/s drop velocity, on the same wafer. This is because both can be made using the same process parameters.

No Misdirected Drops

Misdirected drops are eliminated by the provision of a thin rim around the

nozzle, which prevents the spread of a drop across the printhead surface in regions where the hydrophobic coating is compromised.

Nozzle rim



No Thermal Crosstalk

When adjacent actuators are energized in bubblejet or other thermal inkjet systems, the heat from one actuator spreads to others, and affects their firing characteristics. In Memjet, heat diffusing from one actuator to adjacent actuators affects both the heater layer and the bend-canceling layer equally, so has no effect on the paddle position. This virtually eliminates thermal crosstalk.

No Structural Acoustic Crosstalk

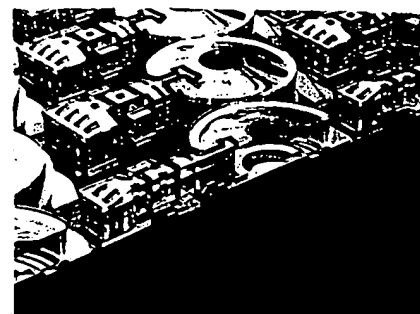
This is a major problem with piezoelectric printheads. It does not occur in Memjet.

No Fluidic Acoustic Crosstalk

Each simultaneously fired nozzle is at the end of a 300 micron long ink inlet etched through the (thinned) wafer. These ink inlets are connected to large ink channels with low fluidic resistance. This configuration virtually eliminates any effect of drop ejection from one nozzle on other nozzles.

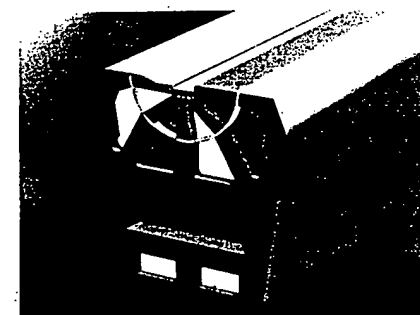
Acoustic crosstalk between 'pods' (groups of nozzles sharing an ink channel) is almost entirely eliminated by the 300 micron long channels opening into relatively large fluid reservoirs. Acoustic crosstalk within a pod is effectively eliminated by the time delay between subsequent drop ejections within a pod. This is typically 20 microseconds, which is more than 40 times longer than the resonant frequency of the ink channel. This gives plenty of time for acous-

tic vibrations to be damped between drop ejections.



No Power Supply Crosstalk

The thick copper bus-bars in the device package, and the active power supply compensation mechanism, effectively eliminate crosstalk coupled through the power supply.



Permanent Printhead

All of the known problems that limit the life of inkjet printheads have been eliminated, allowing the printheads to be permanently installed. This dramatically lowers the production cost of consumables. Note, however, that the selling price of consumables is not necessarily related to the production cost, and need not be reduced.

No Kogation

Kogation (residues of burnt ink, solvent, and impurities, from the Japanese 'koga' for burnt rice) is a significant problem with bubblejet and other thermal inkjet printheads. Memjet does not have this problem, as the ink is not heated.

No Cavitation

Erosion caused by the violent collapse of bubbles is another problem that limits the life of bubblejet and other thermal inkjet printheads. Memjet does not have this problem because no bubbles are formed.

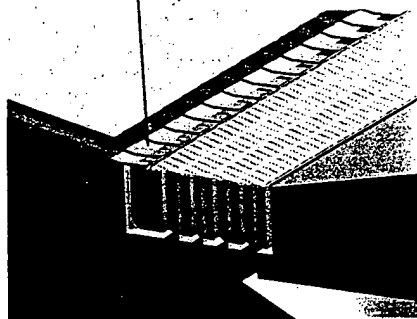
No Electromigration

No metals are used in Memjet actuators or nozzles, which are entirely ceramic. Therefore, there is no problem with electromigration in the actual inkjet devices. The CMOS metallization layers are designed to support the required currents without electromigration. This can be readily achieved because the current considerations arise from heater drive power, not high speed CMOS switching.

Distributed Power Connections

While the energy consumption of Memjet is fifty times less than thermal inkjet, the high print speed and low voltage results in a fairly high electrical current consumption. Worst case current for a photographic Memjet head printing in two seconds from a 3 Volt supply is 4.9 Amps. This is supplied via copper busbars to 256 bond pads along the edge of the chip. Each bond pad carries a maximum of 40 mA. On chip contacts and vias to the drive transistors carry a peak current of 1.5 mA for 1.2 μ s, and a maximum average of 12 mA.

Alternating power and signal connections on TAB film



Close-up cross section of packaged printhead

No Corrosion

The nozzle and actuator are entirely formed of glass and titanium nitride (TiN), a conductive ceramic commonly used for metallization barrier layers in CMOS devices. Both materials are at minimum chemical energy levels with respect to water, so do not corrode. Titanium nitride does not corrode or dissolve in extreme environments such as molten aluminum. It is used as the coating for the electrodes in aluminum smelters. TiN is also highly wear resistant - many watches and jewelry items are coated with TiN as it looks like gold, but has much better wear properties.

TiN does slowly oxidize in air above 500 °C, which limits the efficiency of the actuator, as the actuator efficiency is proportional to its temperature rise.

Greater efficiency can be obtained by the use of (Ti,Al)N, which has similar properties to TiN but resists oxidation up to 900 °C.

No Electrolysis

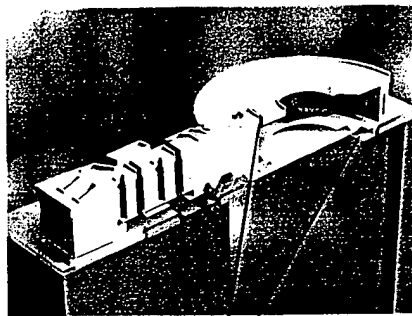
The ink is not in contact with any electrical potentials, so there is no electrolysis. This is achieved by a deliberate design feature in the actuator arm, which is a gap between the actuator loop and the paddle. This electrically isolates the paddle from the drive circuit.

No Fatigue

All actuator movement is within elastic limits, and the materials used are all ceramics, so there is no fatigue. Finite element analysis shows the maximum strain to be 0.5%.

No Friction

No moving surfaces are in contact, so there is no friction.



The actuator and paddle do not contact the nozzle chamber.

No Stiction

'Stiction' is a combination of 'stick-ing' and 'friction', a problem common to many MEMS devices. Memjet is designed to eliminate stiction during the release of the actuators. This is achieved by the low ratio of width to thickness of the cantilever beam, in combination with the high Young's modulus of the TiN layers.

No Crack Propagation

Finite element analysis (FEA) has shown the maximum strain to be 0.5%. This is well within the crack propagation limit of the actuator, with the typical surface roughness of the TiN layers.

No Electrical Poling Required

Piezoelectric materials must be poled after they are formed into the printhead structure. This poling requires very high electrical field strengths - around 20,000 V/cm. The high voltage

requirement typically limits the size of piezoelectric printheads to around 5 cm, requiring 100,000 Volts to pole. Memjet requires no poling.

No Rectified Diffusion

Rectified diffusion - the formation of bubbles due to cyclic pressure variations - is a problem that primarily afflicts piezoelectric inkjets. Memjet is designed to prevent rectified diffusion, as the ink pressure never falls below zero.

Elimination of the Saw Street

The saw street between chips on a wafer is typically 200 microns. This would take 26% of the wafer area. Instead, plasma etching is used, requiring just 4% of the wafer area. This also eliminates breakage during sawing.

Lithography Using Standard Steppers

Although Memjet printhead chips can be as long as the wafer is wide, standard steppers (which typically have an imaging field around 20 mm square) are used. This is because the printhead is 'stitched' using identical half inch exposures. Alignment between stitches fields is not critical, as there are no electrical connections between stitch regions. One segment of each of 32 printheads is imaged with each stepper exposure, giving an 'average' of 4 printheads per exposure.

Integration of Full Color on a Single Chip

Memjet integrates all of the colors required onto a single chip. This cannot be done with pagewidth 'edge shooter' designs, such as Canon Bubblejet.

Wide Variety of Inks

Memjet does not rely on the ink properties for drop ejection. Inks can be based on water, microemulsions, oils, various alcohols, MEK, hot melt waxes, or other solvents. Memjet can be 'tuned' for inks over a wide range of viscosity and surface tension. This is one significant factor allowing a wide range of applications.

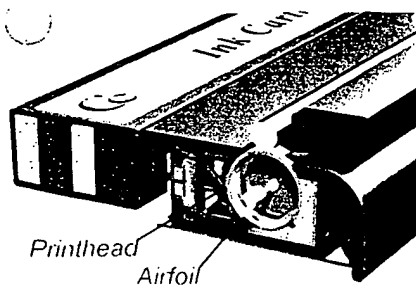
Archival Quality

With the right choice of dye and media, archival permanence significantly better than color photographs can be achieved.

Laminar Air Flow with no Eddies

The printhead packaging is designed to ensure that airflow is laminar, and to eliminate eddies. This is important, as

eddies or turbulence could degrade image quality due to the small drop size.



Printer with controlled airflow

High Drop Repetition Rate can be used

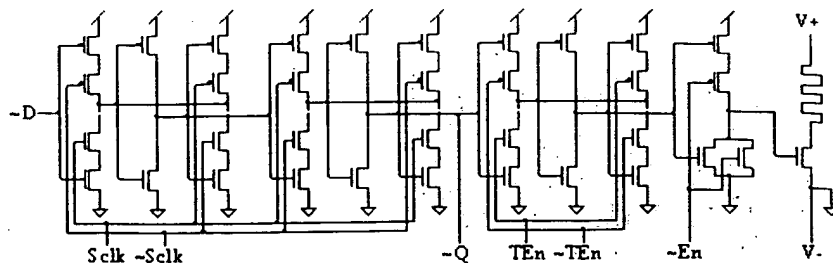
The nominal drop repetition rate of a photographic Memjet is 5 kHz, resulting in a print speed of 2 seconds per photo. The nominal drop repetition rate for an A4 printhead is 10 kHz for 30+ ppm A4 printing. The maximum drop repetition rate is primarily limited by the nozzle refill rate, which is determined by nozzle chamber geometry, flow dynamics, ink pressure, and surface tension. Drop repetition rates of 40 kHz can be achieved (and 100 kHz may be achievable), allowing print speeds of 120 ppm using a single row of nozzles for each color. However, 34 ppm is entirely adequate for most low cost consumer applications.



120 ppm duplex desktop printer

For very high-speed applications, such as commercial printing, multiple printheads can be used in conjunction with fast paper handling. A suitable system for high end commercial printing can use one printhead per color per side. On a 34 inch web, this would give an effective (A4 equivalent) print speed of 10,900 ppm with a 6.25 m/s paper speed.

If the printer speed is reduced, the energy required to print a page is distributed over a longer time, so the power consumption is reduced. For operation from AA batteries this can be important,



Per-nozzle CMOS circuit

as the internal resistance of the batteries limits the available power. The battery lifetime is not an important issue, as hundreds of pages can be printed from one set of batteries. The drop repetition rate can be reduced as low as desired to reduce power consumption, as the CMOS design is fully static.

Low Head-to-Paper Speed

The nominal head to paper speed of a photographic Memjet printhead is only 0.076 m/sec. For an A4 printhead it is only 0.16 m/sec., which is about a third of the typical scanning inkjet head speed. The low speed simplifies printer design and improves drop placement accuracy. However, this head-to-paper speed is enough for 34 ppm printing, due to the pagewidth printhead. Higher speeds can readily be obtained where required.

High Speed CMOS not Required

The clock speed of the printhead shift registers is only 14 MHz for an letter/A4 printhead operating at 30 ppm. For a photographic printer, the clock speed is only 3.84 MHz. This is much lower than the speed capability of the CMOS process used. This simplifies the CMOS design, and eliminates power dissipation problems when printing near-white images.

Fully Static CMOS Design

The shift registers and transfer registers are fully static designs. A static design requires 35 transistors per nozzle, compared to around 13 for a dynamic design. However, the static design has several advantages, including higher noise immunity, lower quiescent power consumption, and greater processing tolerances.

Wide Power Transistor

The width to length ratio of the power transistor is 688. This allows a 4 Ohm on-resistance, whereby the drive transistor consumes 6.7% of the actuator power when operating from 3V. This

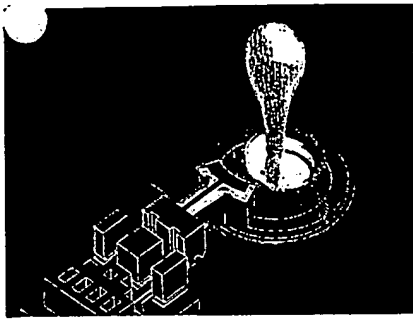
size transistor fits beneath the actuator. Thus an adequate drive transistor, along with the associated data distribution circuits, consumes no chip area that is not already required by the actuator.

There are several ways to reduce the percentage of power consumed by the transistor: increase the drive voltage so that the required current is less, reduce the lithography to less than 0.5 micron, use BiCMOS or other high current drive technology, or increase the chip area, allowing room for drive transistors which are not underneath the actuator. However, the 6.7% consumption of the present design is considered a cost/performance optimum.

Extensive Simulation

Extensive simulations of fluid dynamic, mechanical, thermal, electrical, and other characteristics of the device have been performed. These are done using software developed at Silverbrook Research, in combination with several leading commercial software packages (Ansys, Fidap, and Matlab). Simulation is used as a 'computational microscope' which is able to 'see' microscopic stresses, temperature profiles, and fluid flow in ways impossible with physical experiments. All simulations performed at Silverbrook Research are 'causal'. That is, no assumptions are made about the motion of the ink or other aspects of the device. A simulated voltage pulse is provided to the actuator, and then we watch what happens. Simulations are performed at sufficient resolution to capture the detailed behavior of features such as satellite drops. More than 2,000 simulations have been performed, using more than 20,000 hours.

of compute time on several high performance workstations.



Simulated drop ejection of a Memjet nozzle.

YIELD

Yield is, of course, a critical aspect of manufacturing any chips. For this reason, we have put considerable emphasis on maximizing yield. The base CMOS process is 0.5 micron, a mature technology able to achieve very high yields on reasonable sized chips. The chip size is small: about 8 mm² per 1/2" print head segment (1.3 cm² for an 8" printhead).

The MEMS process itself is not very sensitive to particulate contamination - most feature sizes are well above 1 micron, and most layers are quite insensitive to particulate contamination.

However, it is not a good idea to be complacent about yield, especially for a new process. Accordingly, the yield estimates that we use are pessimistic. The yield is calculated from the defect

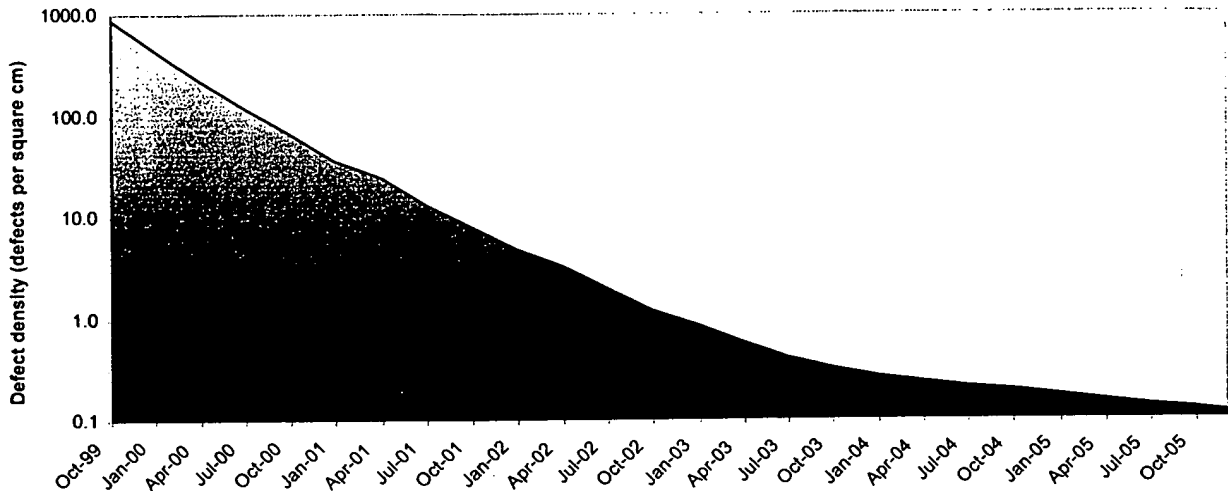
density for four different printhead configurations.

Yield ramp-up

This projection assumes a slow yield ramp-up over around 5 years. It starts with a defect density of more than 100 defects per cm², falling to around 0.2 per cm² by 2005.

Defect Density used for these financial projections (log scale)

(note: these defect density projections are intended as a worst case estimate for conservative financial projections - actual defect densities will probably be much lower)



Redundancy and Fault Tolerance

To allow cost-effective production of printheads in the early years when the defect density is high, redundant printheads can be used.

The business model automatically selects between four configurations of print-head, depending upon how the cost of each configuration changes with

changing yield. These configurations are:

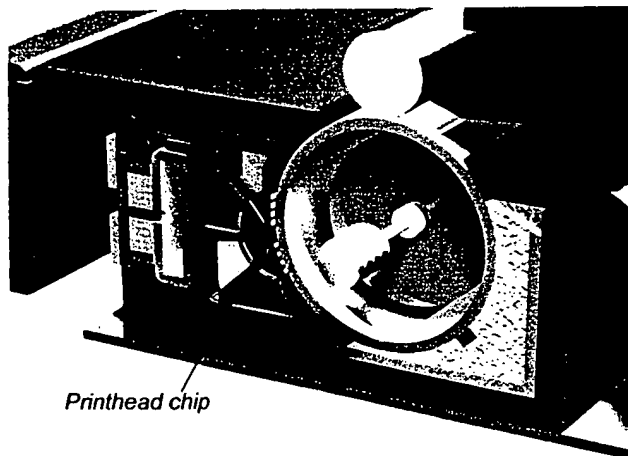
1) A printhead with full redundancy (two complete rows of nozzles) made from tested and matched 1/2" printhead segments (a total of 32 half inch segments).

2) A printhead with full redundancy made from two rows of untested 4"

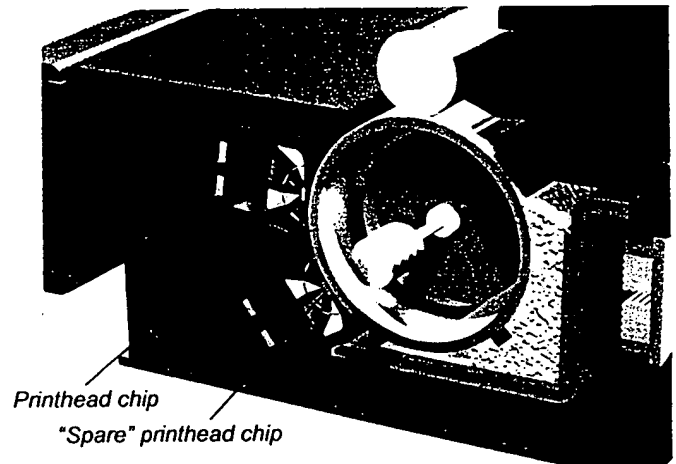
printhead segments (a total of 4 four inch segments).

3) A printhead with no redundancy made from 16 half inch tested segments.

4) A printhead with no redundancy made from 2 four inch tested segments.



Normal printhead configuration with a single set of nozzles (51,200 total nozzles)



Redundant printhead configuration with two sets of nozzles (102,400 total nozzles)

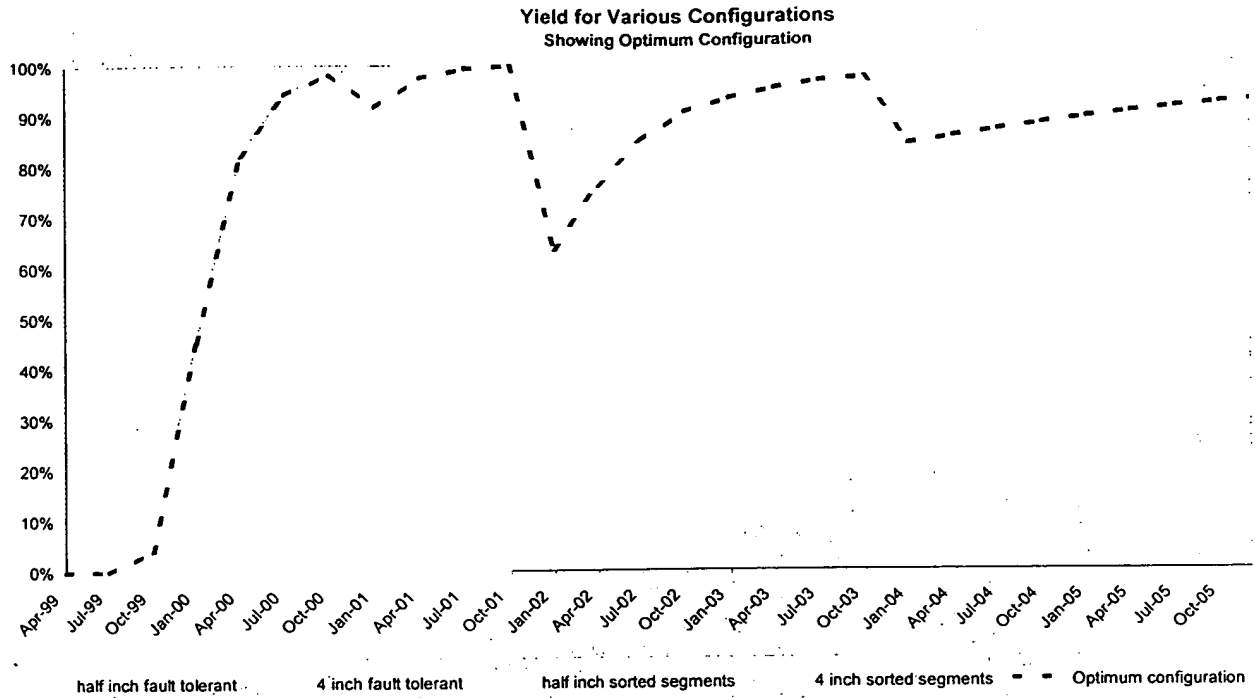
Printhead Yield

The overall printhead yield can be improved dramatically by the use of

redundancy / fault tolerance when the defect densities are high.

The following graph shows the 'sort yield' of 8" printheads of four different

types based on the defect density curve above.

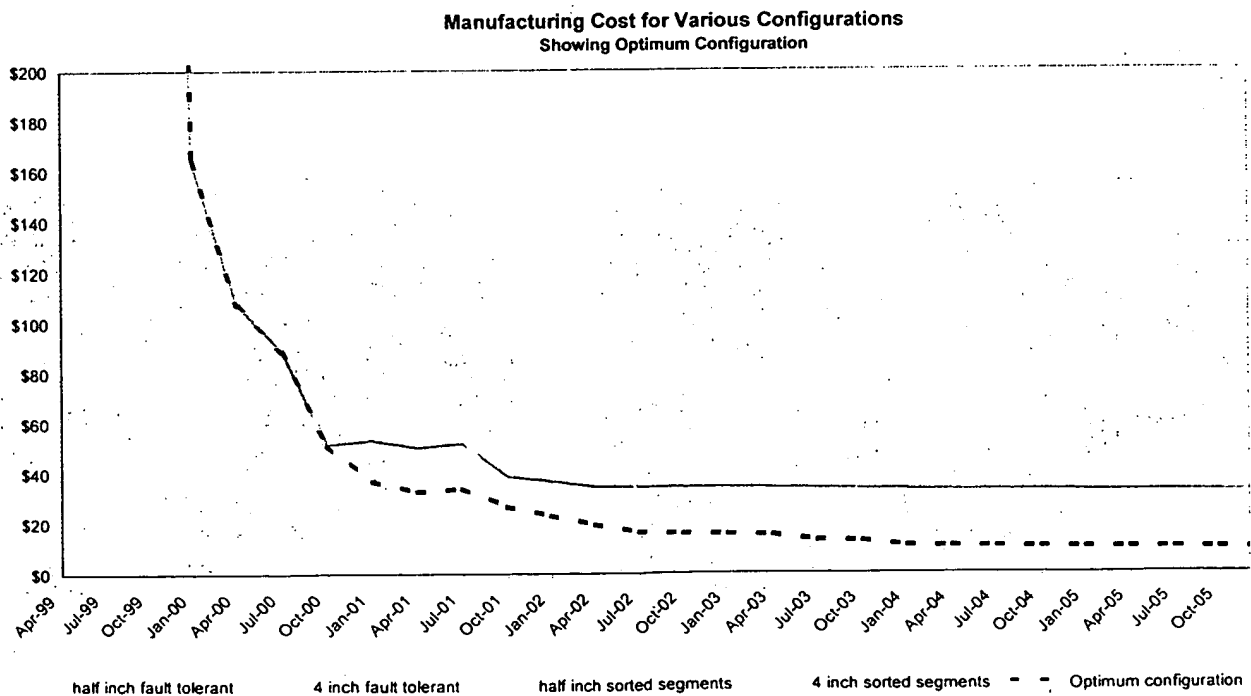


Printhead Manufacturing Cost

The manufacturing cost of the printhead changes with yield. Although the yield of the fault tolerant configurations of printhead will always be higher than non-fault tolerant configurations, fault

tolerance is not cost effective once the defect densities are low enough. The primary reason for this is that two complete sets of nozzles are required for fault tolerance (unlike memories, where a few redundant rows and/or columns are suf-

ficient). The graph below reflects the total manufacturing costs of printheads, including device sorting and packaging. The volume of manufacture is also considered into the cost projection.



VOLUME

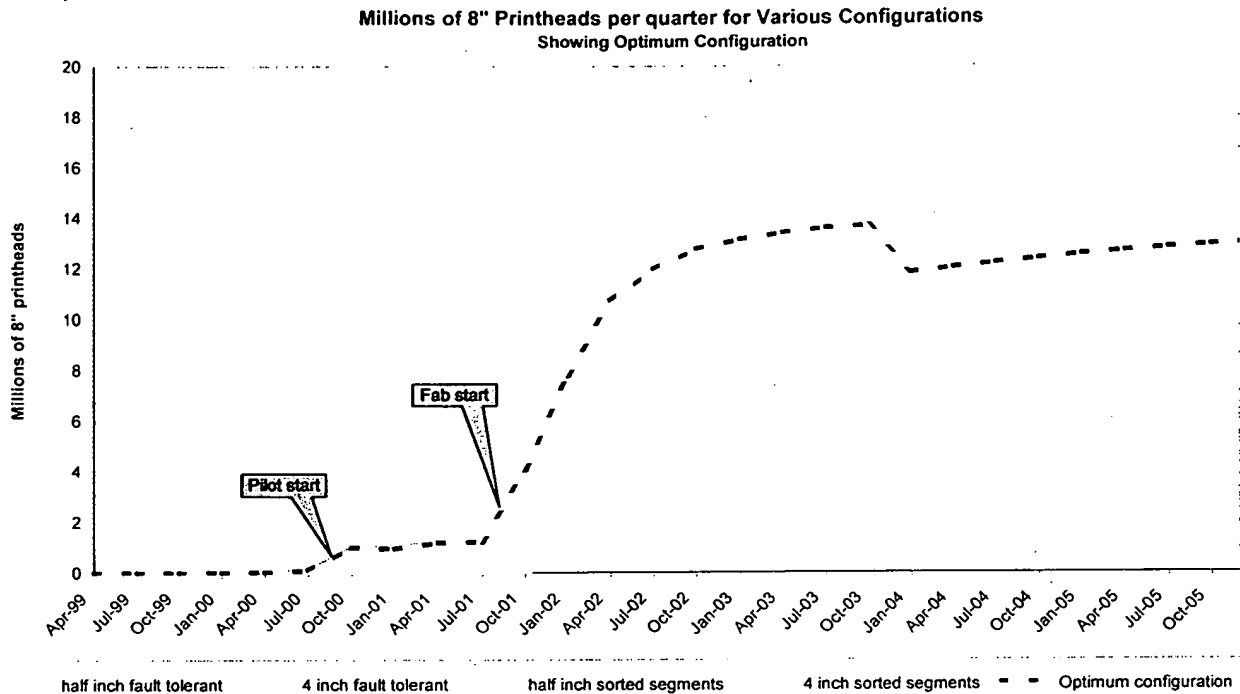
The manufacturing volume is predicted to go through three major phases:

1) An initial lab phase, where only around 100 wafers per month are processed, the yield are low to none, and the available number of printheads is

very limited. Defect densities above 100 per cm^2 are assumed.

2) A pilot phase, where the number of wafers processed each month is 5,000. Defect densities are assumed to be between 10 per cm^2 and 100 per cm^2 , necessitating the use of redundancy to achieve good printhead yields.

3) A full manufacturing phase, where 25,000 wafers are processed each month. Here defect densities are expected to fall from around 8 per cm^2 to 0.1 per cm^2 over the course of five years. During this phase, it is more cost effective *not* to use redundancy.



Early Product Mix

The market focus during the pilot phase and the main production phase should be different. During the pilot phase, markets which are relatively insensitive to print-head cost should be targeted. These include:

- 1) Wide format printing (machine prices around \$10,000)
- 2) Network color printing (machine prices between \$3,000 to \$7,000)
- 3) Digital commercial printing (machine prices \$100,000 and up)
- 4) Photo finishing (machine prices between \$5,000 and \$20,000)

During the main manufacturing phase, high volume markets can also be targeted.

MEMJET PROTOTYPE FABRICATION

Before an integrated CMOS + MEMS prototype is made, we recommend the fabrication of a MEMS only prototype. The MEMS prototype can be made very faithfully to a full print head, with nearly identical actuator and nozzle structure. The main limitation of a MEMS only prototype is that the number of nozzles is limited, as a separate bond pad is required for each nozzle.

The prototype described here has only 15 nozzles per chip. The behavior of a few groups of 5 nozzles is a near perfect model of the entire chip performance, as the fluidic, thermal, electrical, acoustic, or mechanical coupling between 5 nozzle groups is extremely small.

A chip layout with 15 nozzles is shown below. This chip is 3 mm x 3 mm, and is replicated on a 1.2 x 1.2 cm mask set. The mask set contains 10 variants of the precise nozzle dimensions,

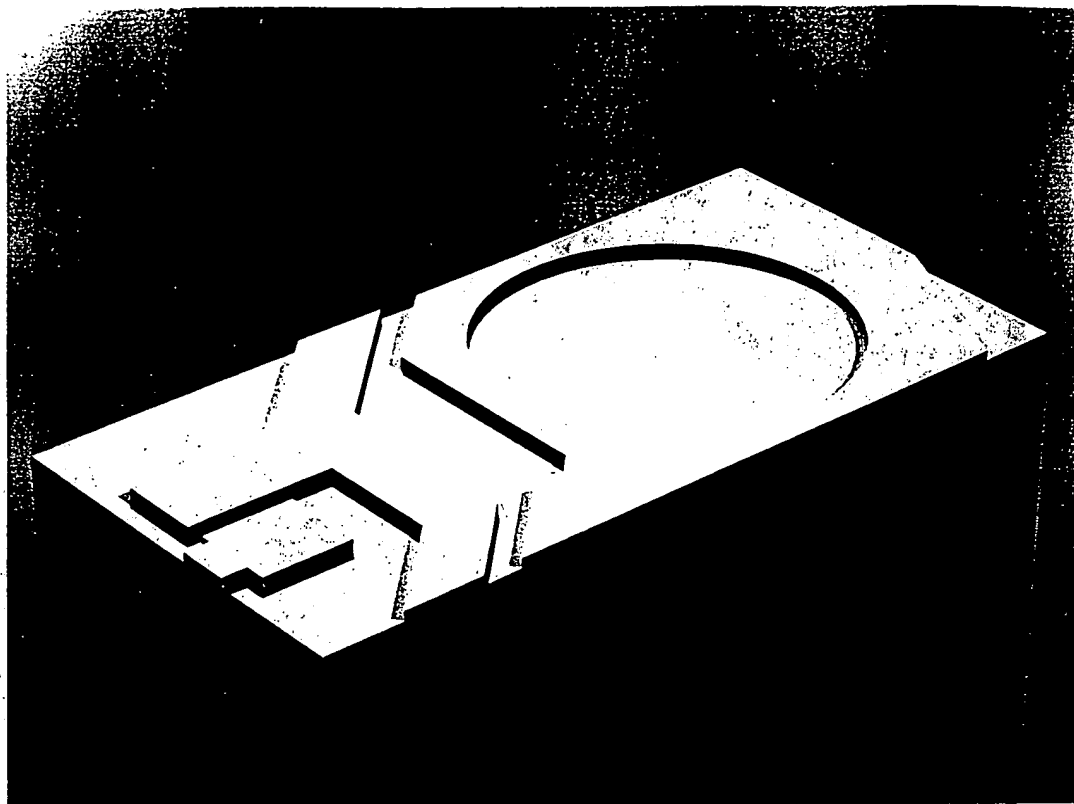
plus various test structures. The mask also contains a test printhead with around 3000 nozzles. As there is no CMOS on the chip, only some of the nozzles are 'wired up'. This chip is intended to test mechanical aspects of handling and packaging.

The mask has been laid out using 'Tanner Tools', and is available as Tanner or GDSII files.

The subsequent pages show the process steps, and the mask for a single nozzle unit cell.



1) 1 Micron Aluminum



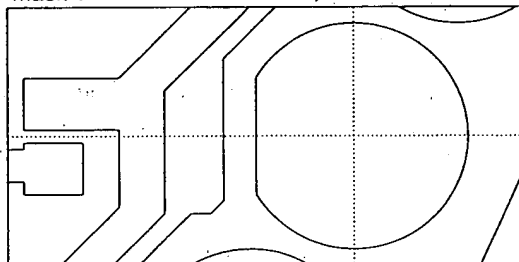
PROCESS DETAILS

One micron of aluminum is deposited and etched using Mask 1. This mask includes the electrodes to the actuator, the bond pads, and the wiring between these items. It is possible to replace the aluminum with TiN wiring and bond pads. However, that would diverge further from the CMOS + MEMS design, and add process risks. The region around the nozzle chamber is on Metal1 for a 1P2M CMOS + MEMS process, while the electrodes are on metal 2.

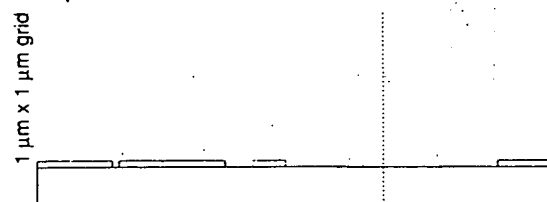
Layer thickness	1 micron (nominal)
Thickness variation	± 50%
Linewidth	3 microns
CD Accuracy	± 0.2 microns
Alignment accuracy	Mechanical
Align to	Wafer flat
Production process	CMOS M1 and M2
Production mask	Contains wiring



Mask 1

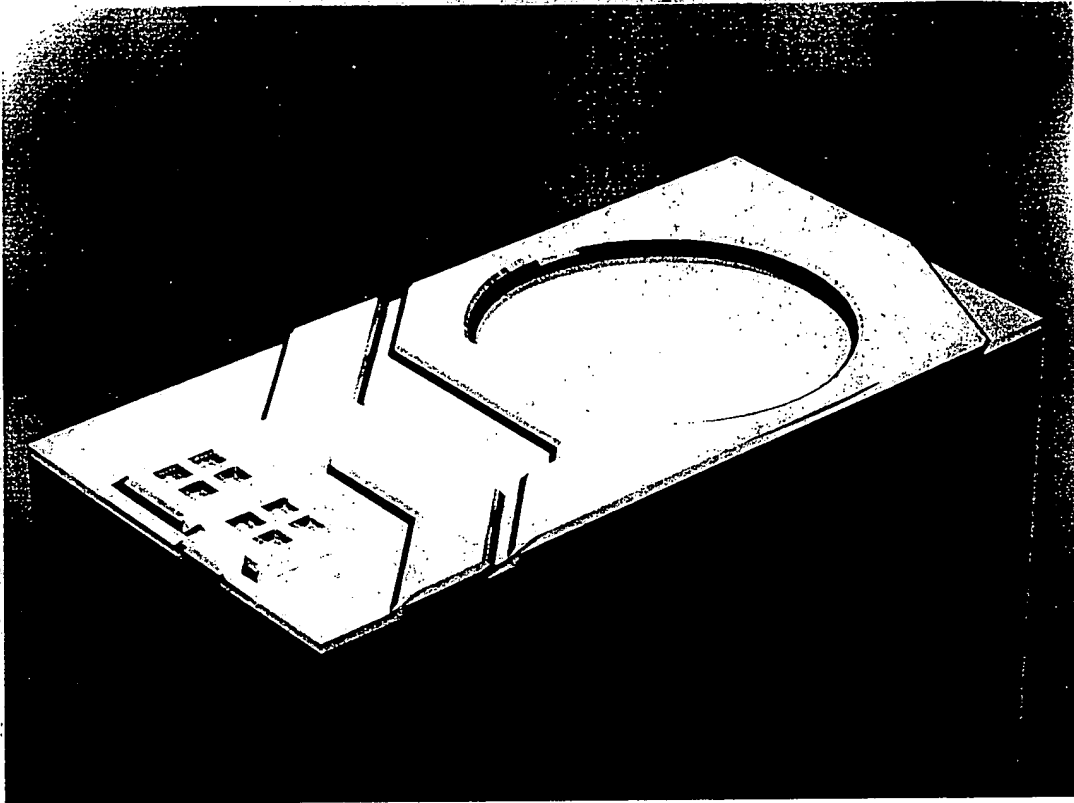


Top View



Deposit and etch 1 micron aluminum

2) 1 Micron PECVD Nitride

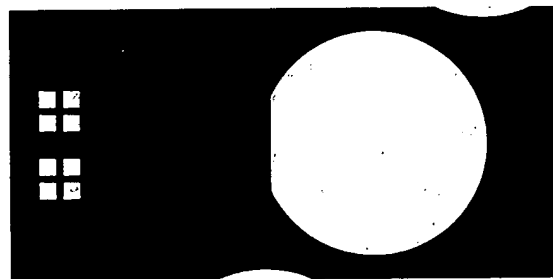


PROCESS DETAILS

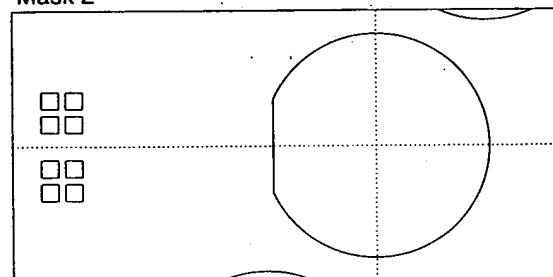
One micron of PECVD silicon nitride is deposited and etched using Mask 2. This mask includes the vias from the aluminum to the first TiN layer, and some relatively minor fluid control aspects. For a CMOS + MEMS process, this is the passivation layer, and will typically be 0.5 microns of glass followed by 0.5 microns of silicon nitride.

A pure nitride passivation layer is preferable, to prevent ions from the ink from diffusing through the glass.

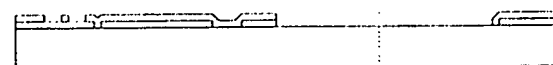
Layer thickness	1 micron
Thickness variation	± 20%
Linewidth	1 micron
CD Accuracy	± 0.2 microns
Alignment accuracy	± 0.2 microns
Align to	Metal 1
Production process	CMOS passivation
Production mask	Same



Mask 2

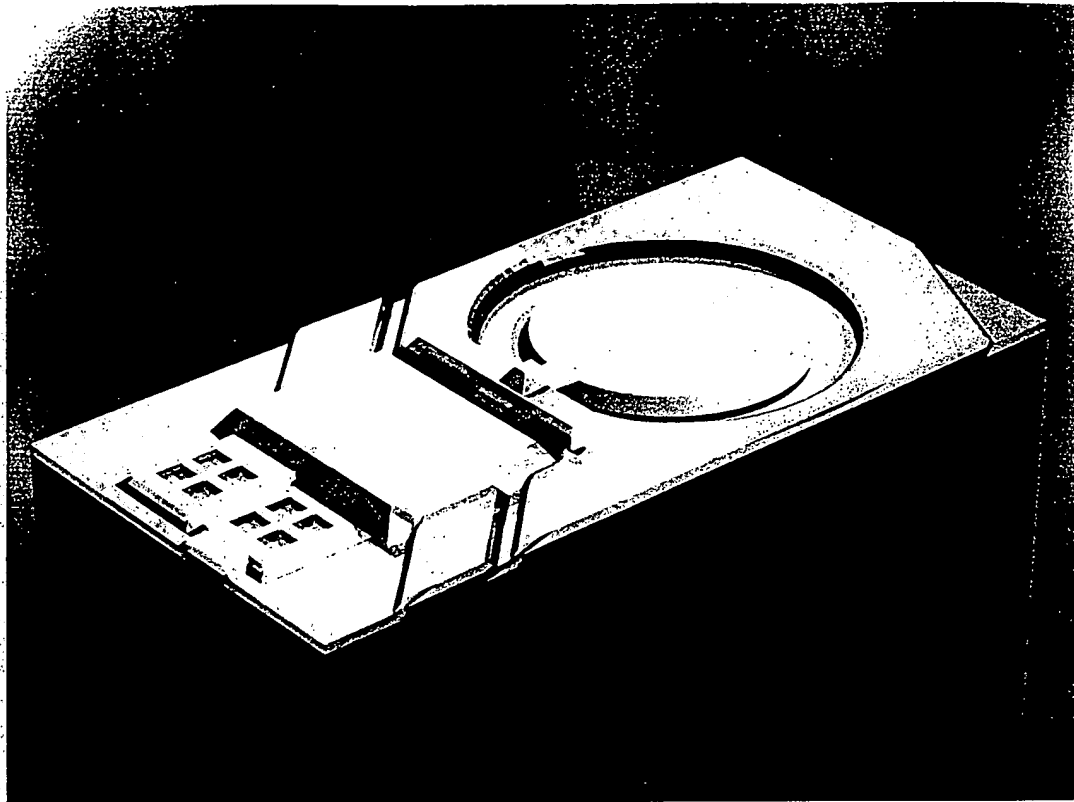


Top View



Deposit and etch 1micron PECVD $\text{Si}_x\text{N}_y\text{H}_z$

3) 1.5 Microns Sacrificial Polyimide

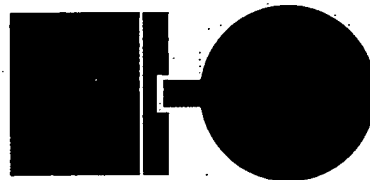


PROCESS DETAILS

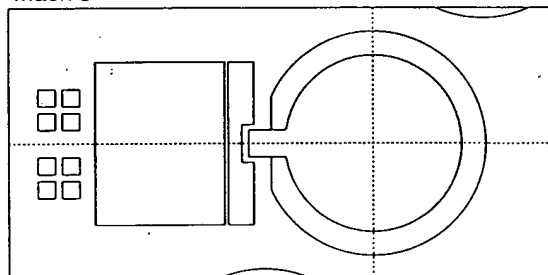
1.5 microns of spin-on photosensitive polyimide is deposited and exposed using UV light to Mask 3. The polyimide is then developed and hardbaked. 1.5 microns is the final thickness - around 3 microns of liquid is spun on, depending upon shrinkage.

The polyimide is sacrificial, so there is a wide range of alternative materials which can be used, such as glass or aluminum. Photosensitive polyimide simplifies the processing, as it eliminates deposition, etching, and resist stripping steps.

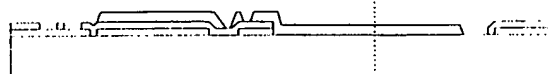
Layer thickness	1.5 microns
Thickness variation	$\pm 10\%$
Polyimide sidewalls	approx. 60°
Linewidth	1.25 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.15 microns
Align to	Metal 1
Production process	Same
Production mask	Same



Mask 3

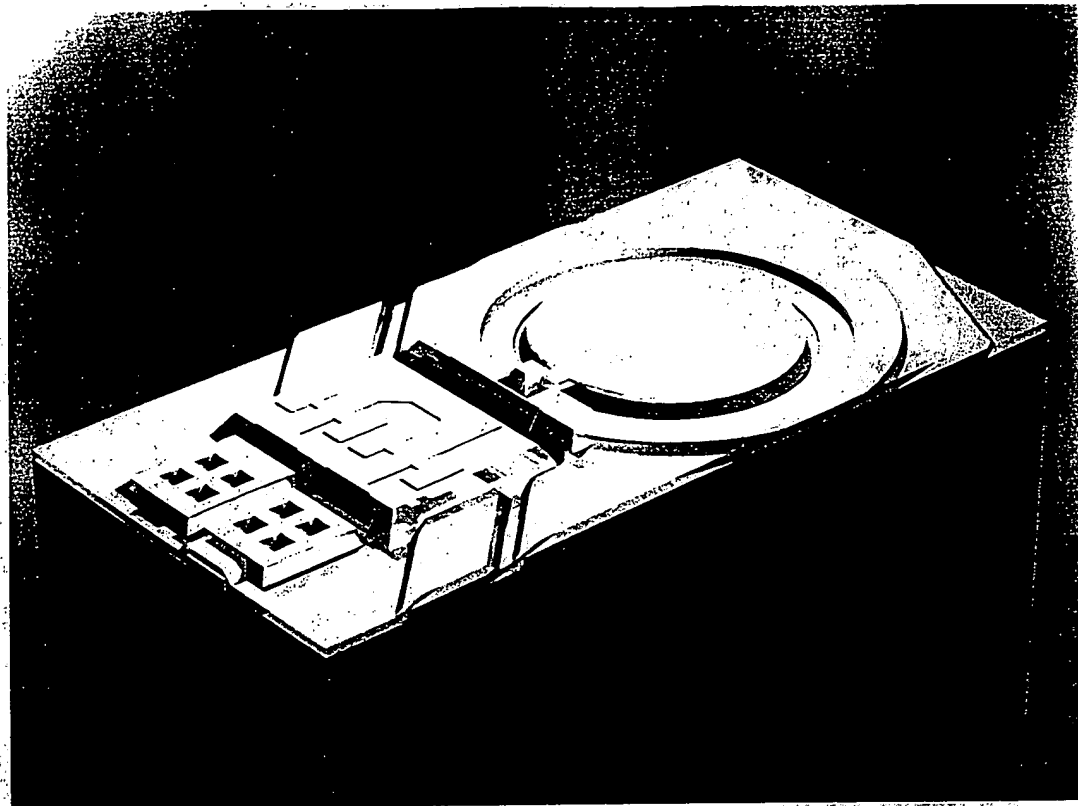


Top View



1.5 microns sacrificial photosensitive polyimide

4) Sputter 0.2 Microns TiN or (Ti,Al)N



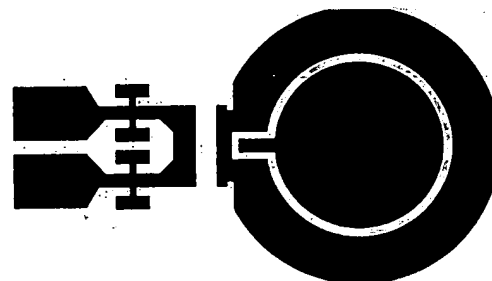
PROCESS DETAILS

0.2 microns of magnetron sputtered titanium nitride is deposited at 300 °C and etched using Mask 4. This layer contains the actuator and part of the paddle.

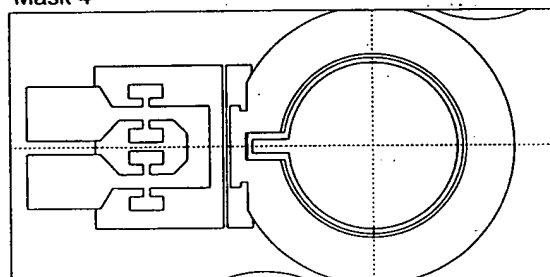
In production, the resistivity of this layer of TiN should be consistent to within a few percent over the wafer.

(Ti,Al)N is preferred to TiN for high efficiency operation, as it resists oxidation at higher temperatures.

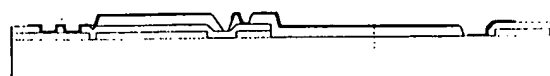
Layer thickness	0.2 microns
Thickness variation	± 5%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.1 microns
Align to	Metal 1
Production process	Same
Production mask	Same



Mask 4

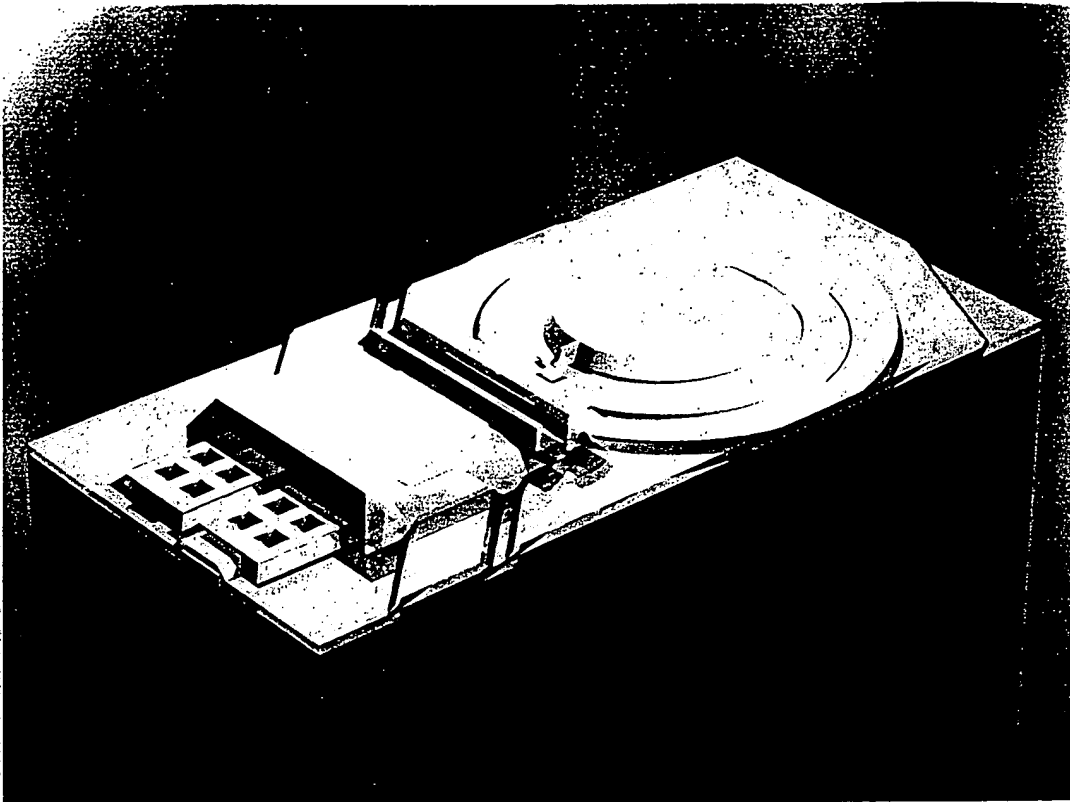


Top View



0.2 microns TiN sputtered at 300 degrees C

5) 1.5 Microns Sacrificial Polyimide



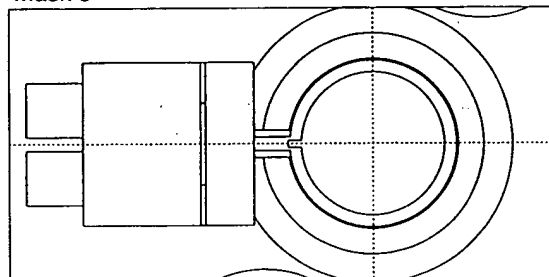
PROCESS DETAILS

This step is identical to step 3.

1.5 microns of spin-on photosensitive polyimide is deposited and exposed using UV light to Mask 5. The polyimide is then developed and hardbaked. 1.5 microns is the final thickness - spin on around 3 microns depending upon shrinkage. The thickness determines the gap between the actuator and compensator TiN layers, so has an effect on the amount that the actuator bends.

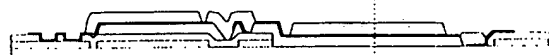


Mask 5



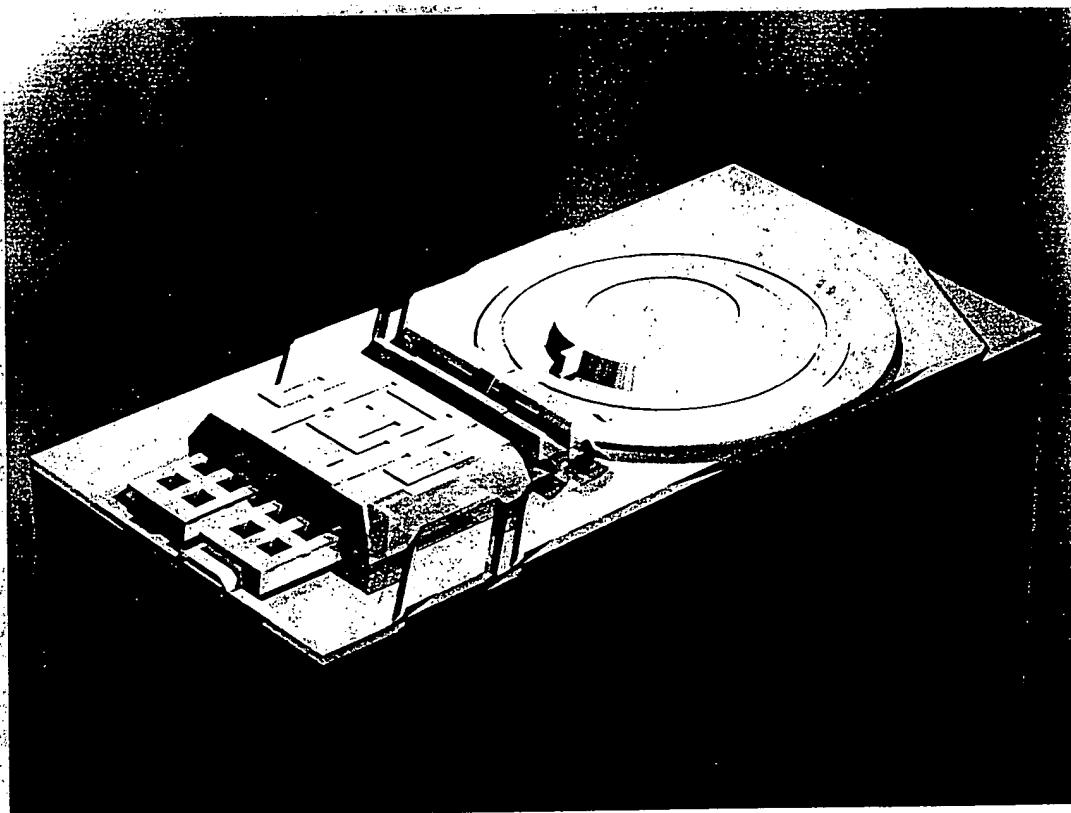
Top View

Layer thickness	1.5 microns
Thickness variation	$\pm 10\%$
Polyimide sidewalls	approx. 60°
Linewidth	1 micron
CD Accuracy	± 0.5 microns
Alignment accuracy	± 0.4 microns
Align to	Metal 1
Production process	Same
Production mask	Same



1.5 microns sacrificial photosensitive polyimide

6) 0.2 Microns Sputtered TiN



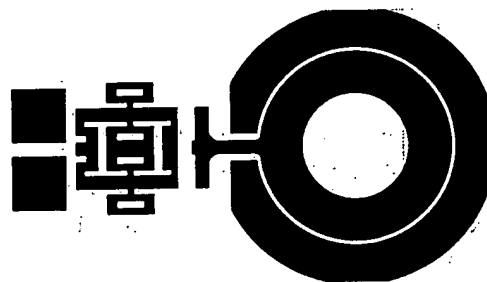
PROCESS DETAILS

This step may be identical to step 4. However, there is no efficiency advantage in the use of (Ti,Al)N, as this layer is not part of the thermal actuator. Either TiN or (Ti,Al)N may be used equivalently.

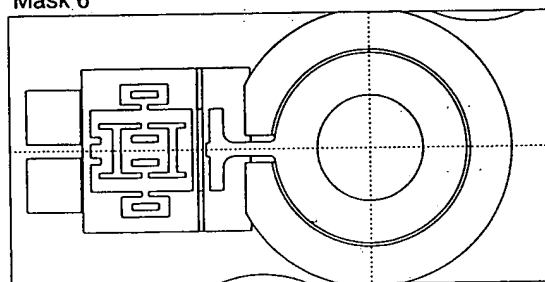
Deposit 0.2 microns of magnetron sputtered titanium nitride, at 300 °C. The TiN is etched using Mask 6.

This layer is not electrically connected, and is used purely as a mechanical component.

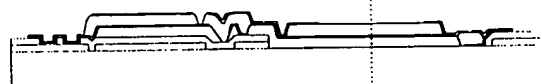
Layer thickness	0.2 microns
Thickness variation	± 5%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.15 microns
Align to	TiN 1
Production process	Same
Production mask	Same



Mask 6

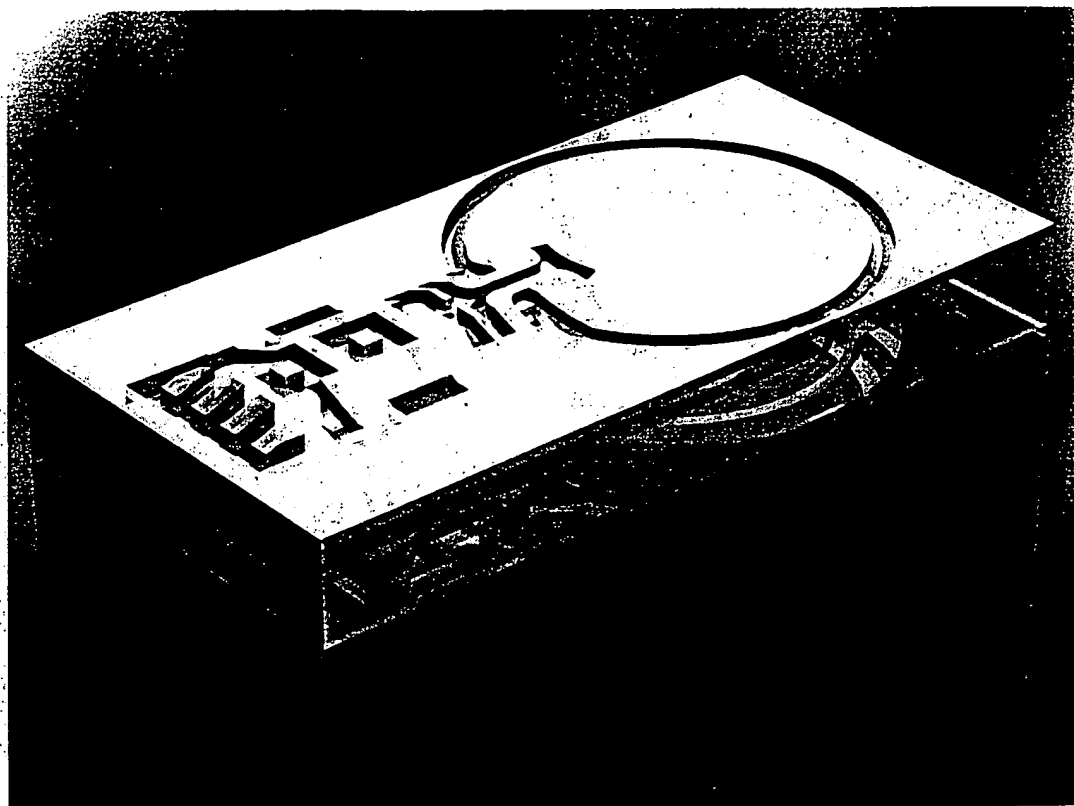


Top View



0.2 microns TiN sputtered at 300 degrees C

7) 8 Microns Sacrificial Polyimide, Al Mask

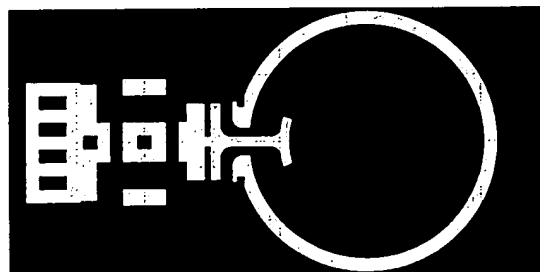


PROCESS DETAILS

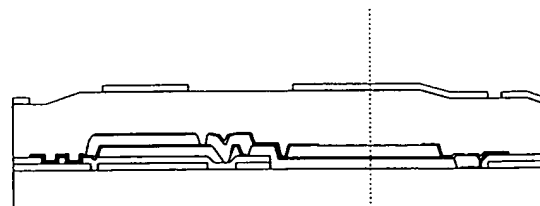
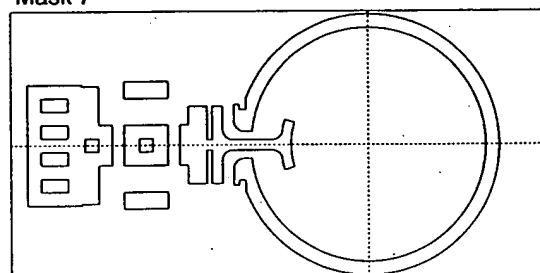
8 microns of standard polyimide is spun on and hardbaked. This thickness determines the height to the nozzle chamber roof. As long as this height is above a certain distance (determined by drop break-off characteristics), then the actual height is of little significance. As this polyimide layer is not photosensitive, it may be a filled layer to obtain a lower coefficient of thermal expansion.

A 50 nm aluminum hard mask is deposited. One micron of resist is spun on and exposed to Mask 7. The Al hardmask is etched.

Layer thickness	8 microns
Thickness variation	+ 4, - 0.5 microns
Linewidth	2 microns
CD Accuracy	± 0.5 microns
Alignment accuracy	± 0.1 microns
Align to	TiN 1
Production process	Same
Production mask	Depends on etch

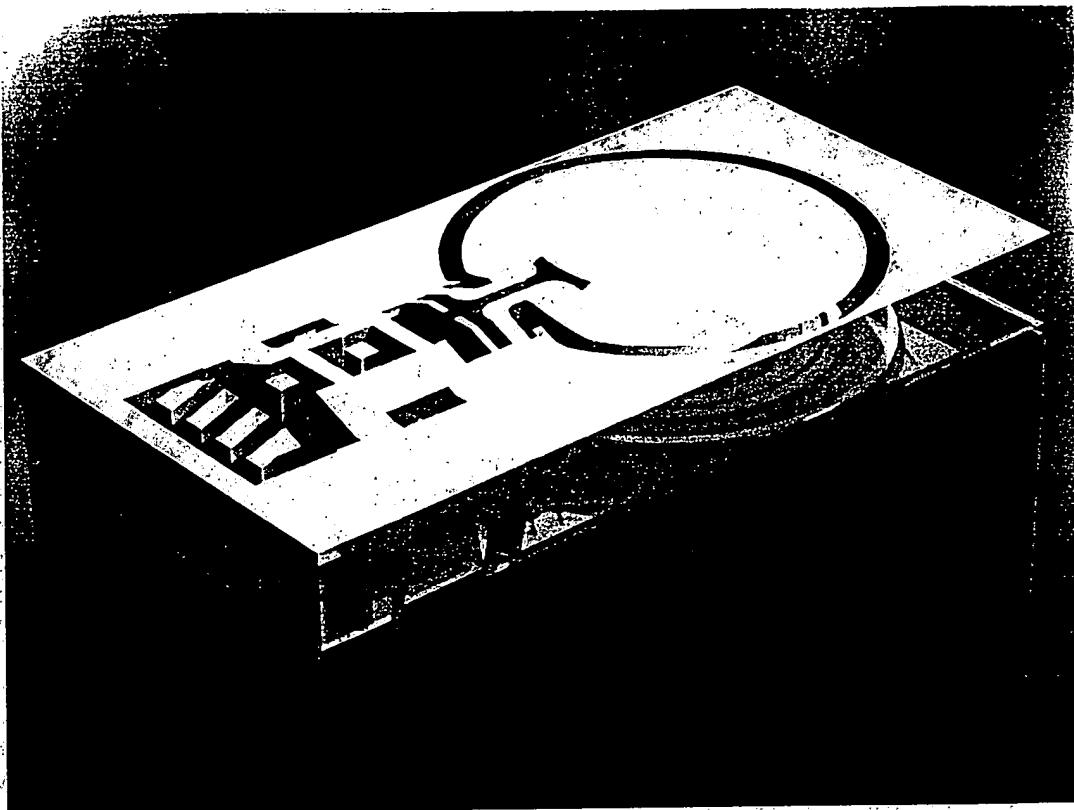


Mask 7



8 microns sacrificial polyimide, with aluminum mask

8) Etch Polyimide using Oxygen Plasma

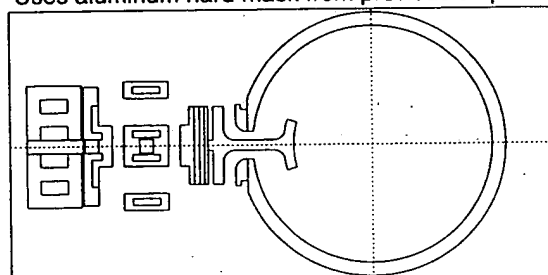


PROCESS DETAILS

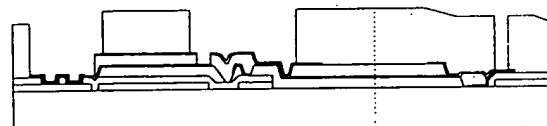
Sacrificial polyimide is anisotropically plasma etched. The sidewall angle should be better than 80 degrees. The mask design shown for Mask 7 is for 90 degree sidewalls, and should be modified to suit the etch process if the etch process used varies more than ± 3 degrees from vertical.

Etch depth	11 microns
Etch stop	TiN, Si_3N_4
Sidewall angle	90 degrees
Angle accuracy	± 3 degrees
Alignment accuracy	± 0.2 microns
Align to	TiN 2
Production process	Same

Uses aluminum hard mask from previous step

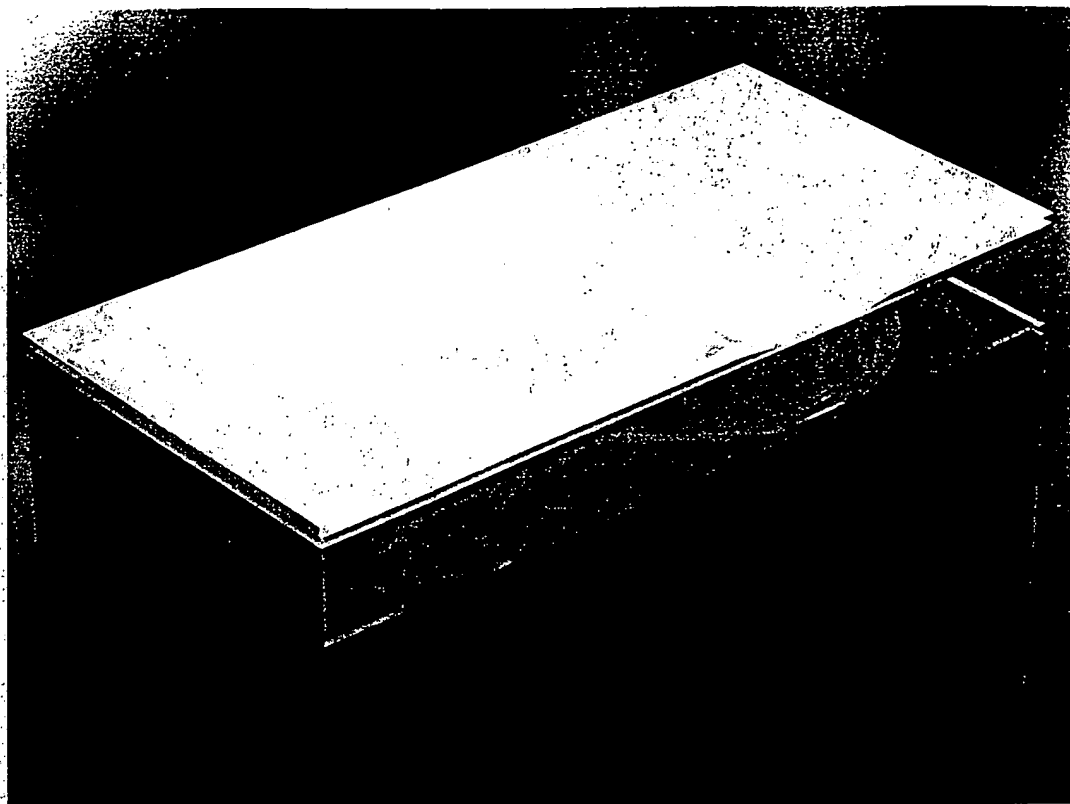


Top View



Etch sacrificial polyimide using oxygen plasma

9) 1 Micron Conformal Silicon Nitride



PROCESS DETAILS

1 micron of PECVD silicon nitride is deposited at 300 °C. This fills the channels formed in the previous PS polyimide layer, forming the nozzle chamber.

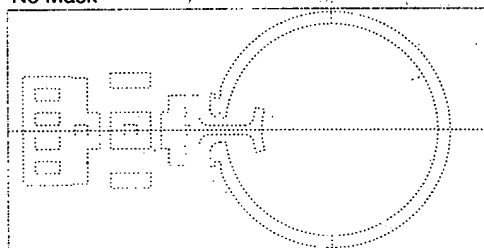
In the cross section, some areas appear to be large solid areas of nitride. These are actually 2 micron thick slots viewed side on.

This layer is not particularly critical. The major requirement is good adhesion to TiN. Enclosed vacuoles should not cause problems.

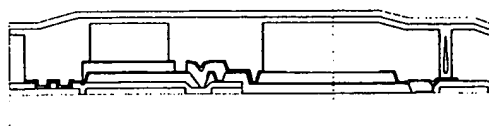
The nitride deposition is followed by 1 micron of polyimide, which is hardbaked.

Si ₃ N ₄ thickness	1 micron
Thickness variation	+/- 25%
Polyimide thickness	1 micron
Thickness variation	+/- 25%
Production process	Same

No Mask

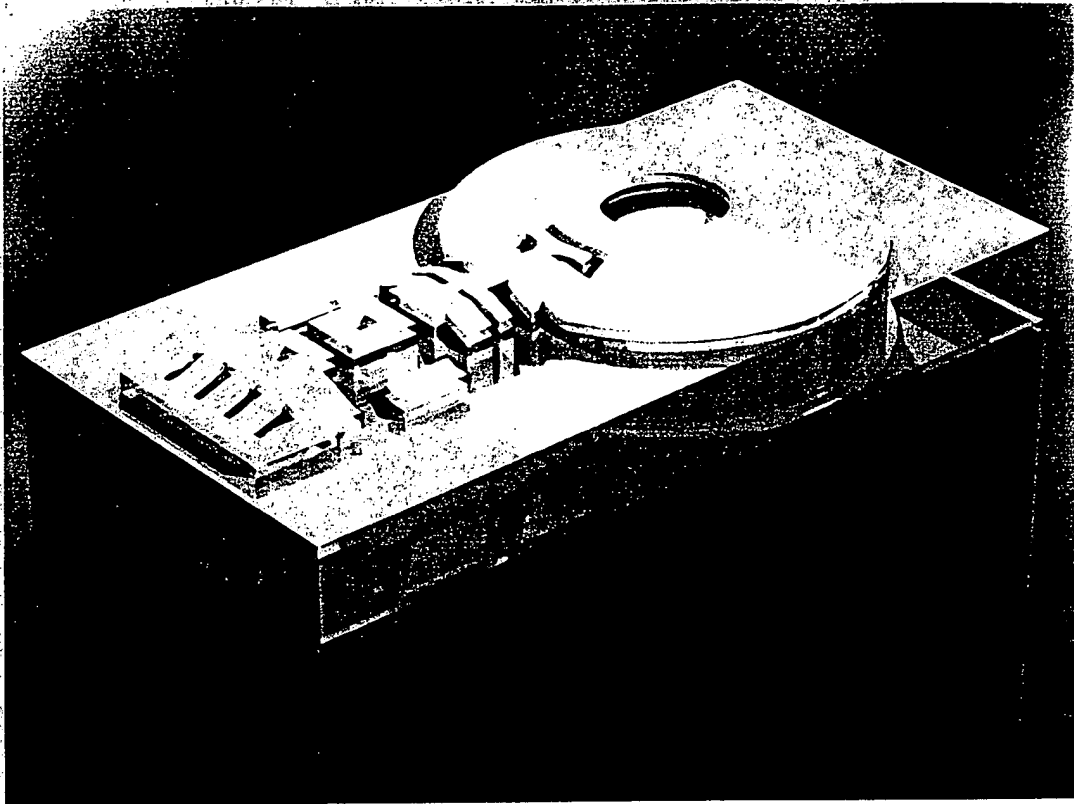


Top View



1 micron conformal PECVD Si₃N₄H₂, 1 micron polyimide

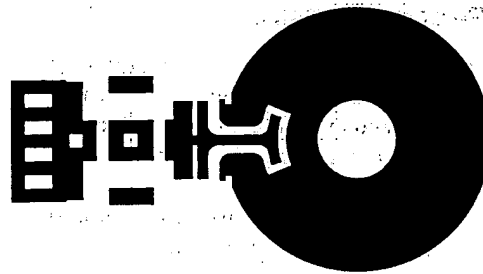
10) Etch Polyimide and Nitride



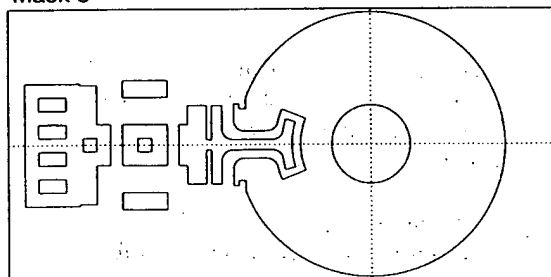
PROCESS DETAILS

The polyimide is etched down to nitride using Mask 8. The nitride is then etched down to Sac 3 polyimide using the Sac 4 polyimide as a mask.

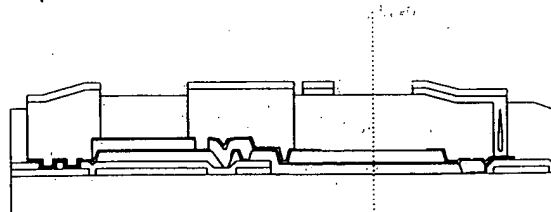
PI Etch depth	1.5 micron
Etch variation	± 10%
Nitride Etch depth	1.5 micron
Etch variation	± 10%
Linewidth	1 micron
CD Accuracy	± 0.15 microns
Alignment accuracy	± 0.1 microns
Align to	TiN 2
Production process	Same
Production mask	Same



Mask 8

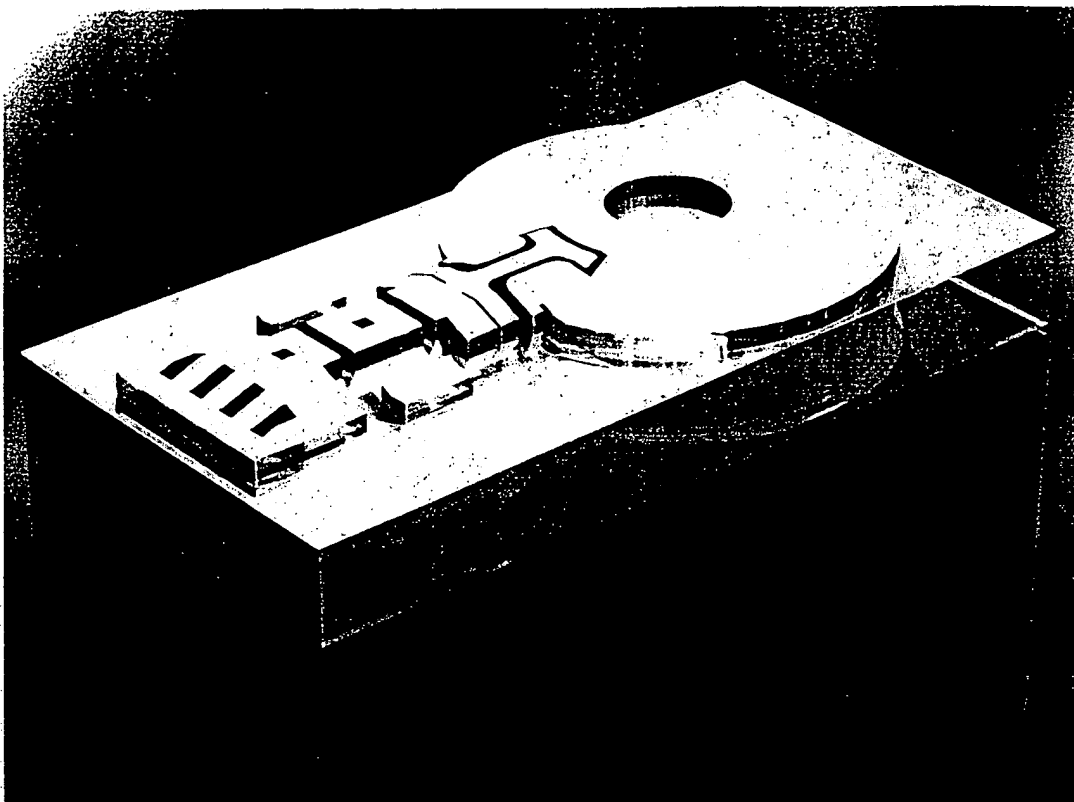


Top View



Etch of Sac 4 polyimide and nozzle roof $\text{Si}_x\text{N}_y\text{H}_z$

11) Deposit 0.25 Microns of PECVD Nitride



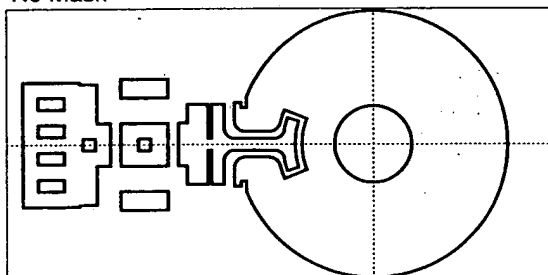
PROCESS DETAILS

0.25 microns of conformal PECVD silicon nitride is deposited at 300°C.

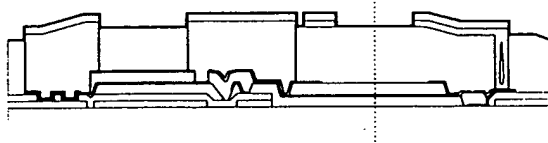
This layer forms the nozzle rims, using a 'sidewall spacer' like process. The thickness is not particularly critical, and could be substantially thinner if desired, as there is insignificant fluidic pressure acting on the rim.

Si ₃ N ₄ thickness	nominal 0.25 microns
Thickness variation	± 25%
Production process	Same

No Mask

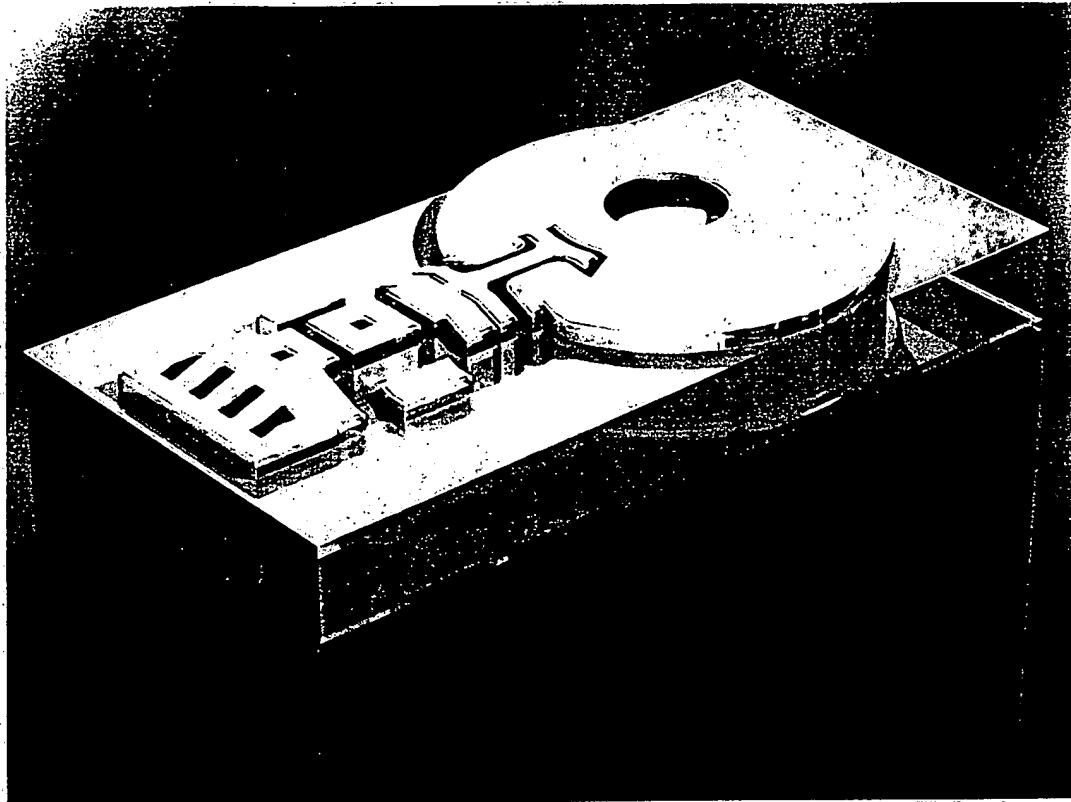


Top View



Deposit 0.25 microns of PECVD Si_xN_yH_z

12) Anisotropic Etch of Nitride

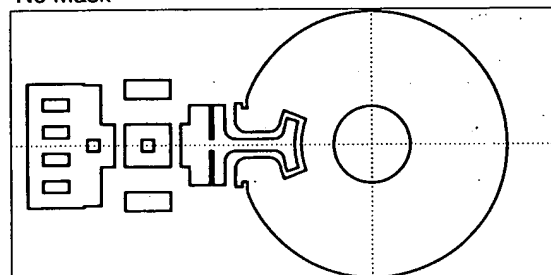


PROCESS DETAILS

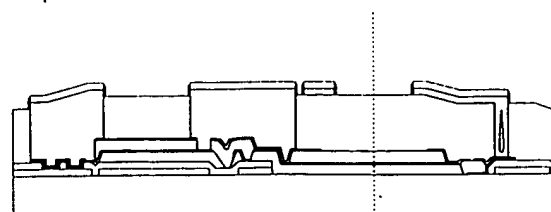
The nozzle rim nitride is anisotropically plasma etched. The etch can be timed, as etch depth is not critical. Substantial overetch is required to ensure that only vertical nitride walls remain, and that nitride over sloping topography is completely removed.

Etch depth	0.5 microns
Depth variation	$\pm 20\%$
Production process	Same
Production mask	None

No Mask

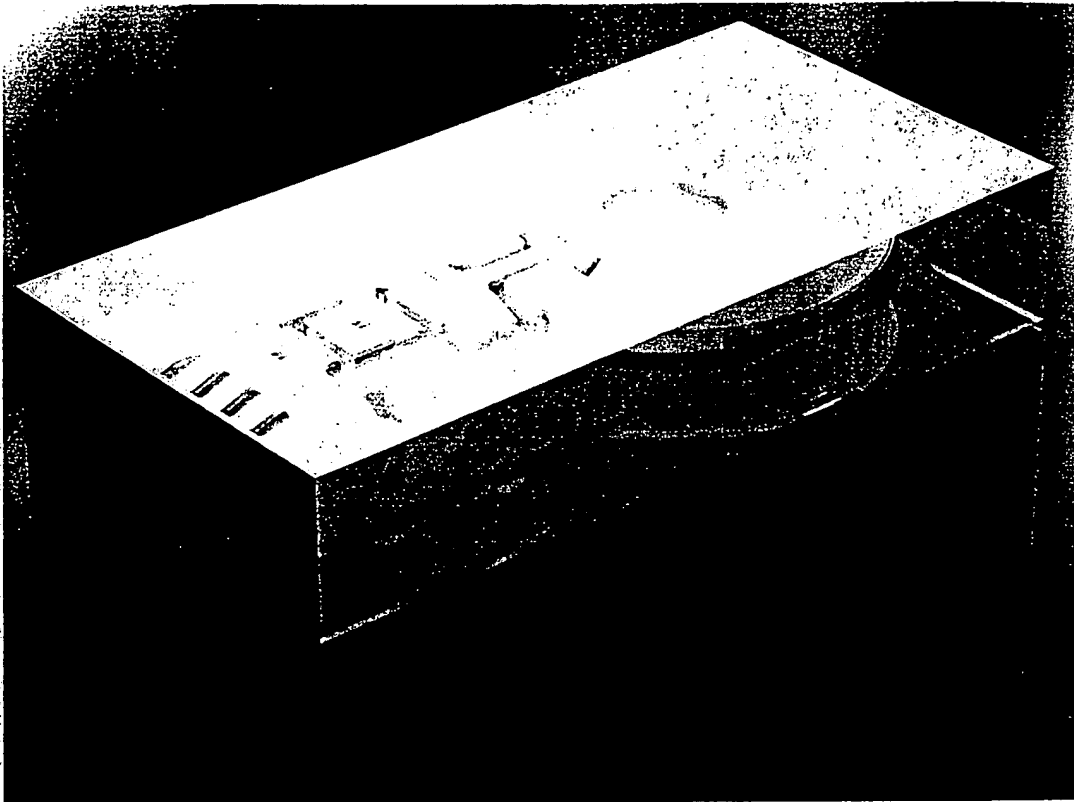


Top View



0.5 micron anisotropic 'sidewall' etch of $\text{Si}_x\text{N}_y\text{H}_z$

13) 4 Microns of Softbaked Resist



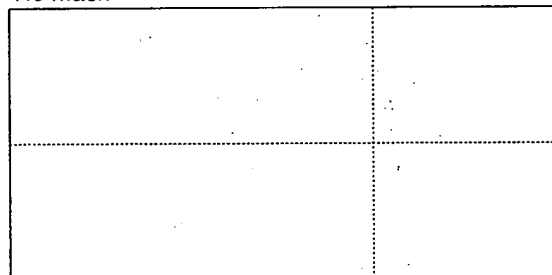
PROCESS DETAILS

Spin on 4 microns of resist and softbake.

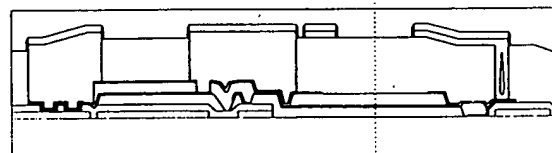
This resist layer is to protect the front side of the wafer during backetch. The resist thickness is to cover the topography of the MEMS devices, and thereby allow a vacuum chuck to be used.

Resist thickness	4 microns nominal
Thickness variation	+50% - 25%
Production process	Same
Production mask	None

No Mask

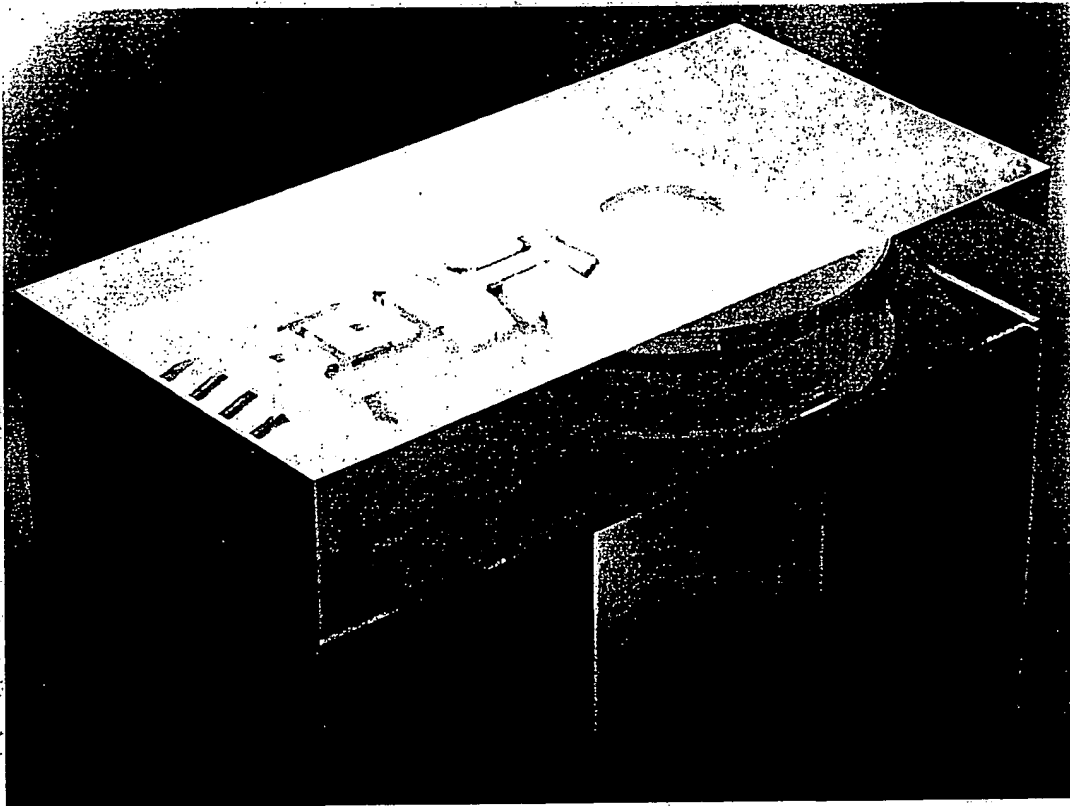


Top View



4 microns softbaked resist as a protective layer

14) Back-etch using Bosch Process



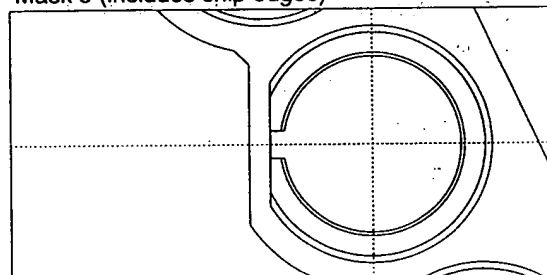
PROCESS DETAILS

The wafer is thinned to 300 microns (to reduce back-etch time), and 3 microns of resist on the back-side of the wafer is exposed to Mask 10. Alignment is to metal 1 on the front side of the wafer. This alignment can be achieved using an IR microscope attachment to the wafer aligner. The wafer is then placed on a platter and etched to a depth of 330 microns (allowing 10% overetch) using the deep silicon etch "Bosch process". This process is available on plasma etchers from Alcatel, PlasmaTherm, and Surface Technology Systems.

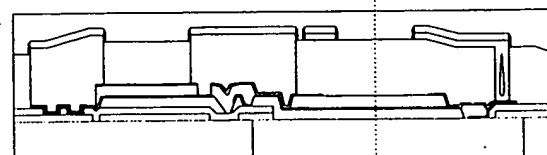
Etch depth	330 micron
Etch variation	$\pm 10\%$
Linewidth	40 microns
CD Accuracy	± 2 microns
Alignment accuracy	± 2 microns
Align to	Metal 1
Production process	Same
Production mask	Full wafer



Mask 9 (includes chip edges)

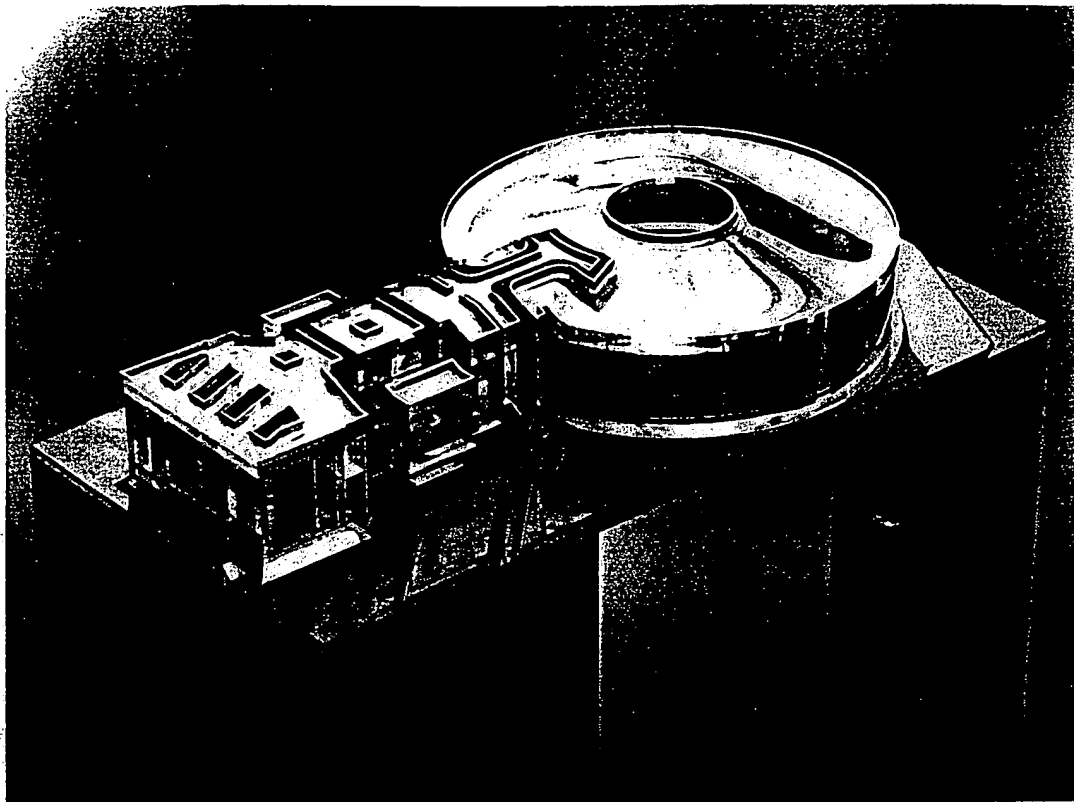


Bottom View, rotated around horizontal axis



Back-etch through wafer using Bosch process

15) Strip all Sacrificial Material

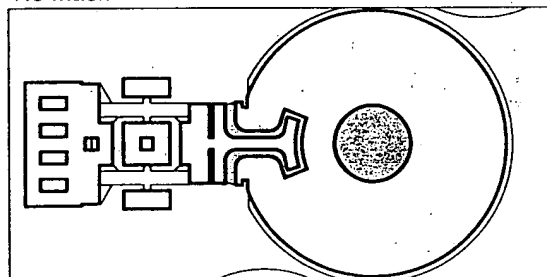


PROCESS DETAILS

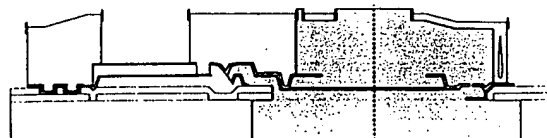
The chips were diced by the previous Bosch process back-etch. However, the wafer is still held together by 11 microns of polyimide. The wafers must now be turned over. This can be done by placing a tray over the wafer on the platter, and turning the whole assembly (platter, wafer and tray) over while maintaining light pressure. The platter is then removed, and the wafer (still in the tray) is placed in the oxygen plasma chamber.

All of the sacrificial polyimide is ashed in an oxygen plasma.

No Mask

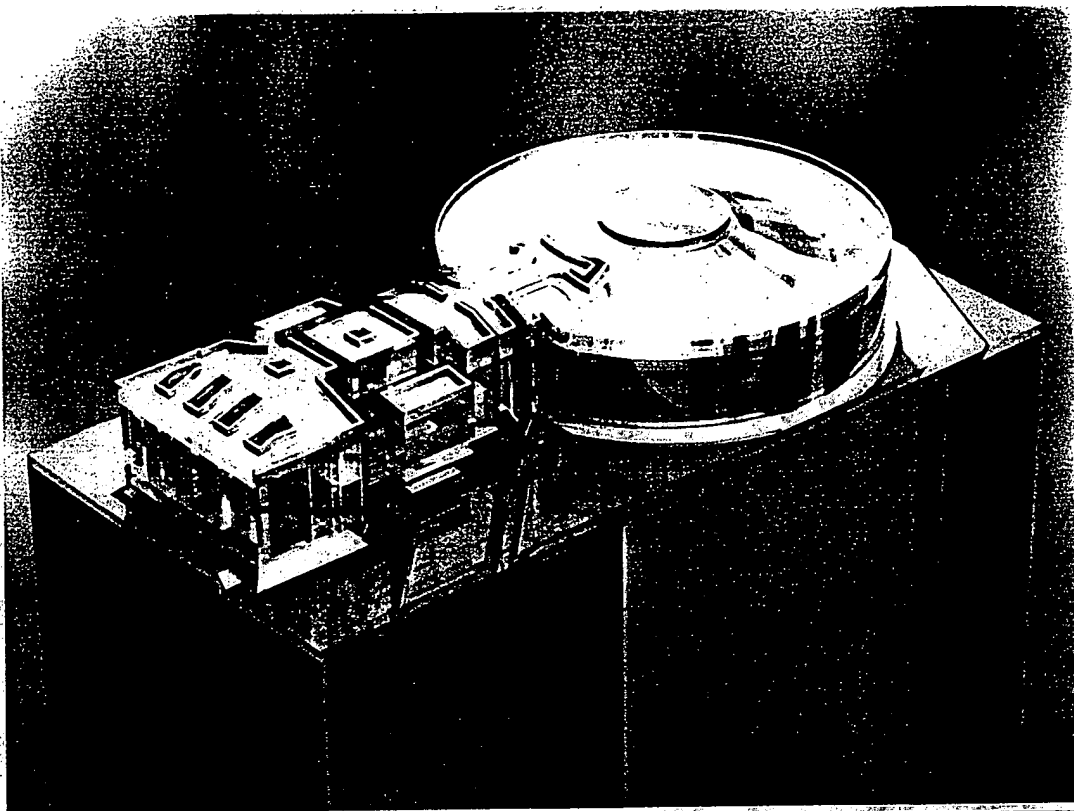


Top View



Package, bond, prime, and test

16) Package, Bond, and Prime.

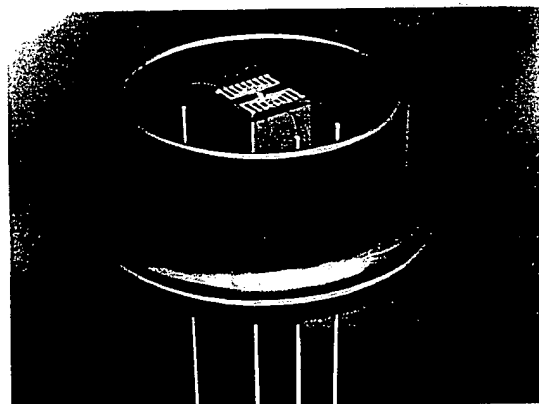
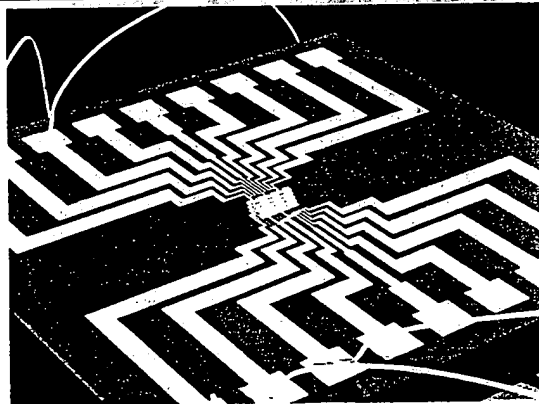


PROCESS DETAILS

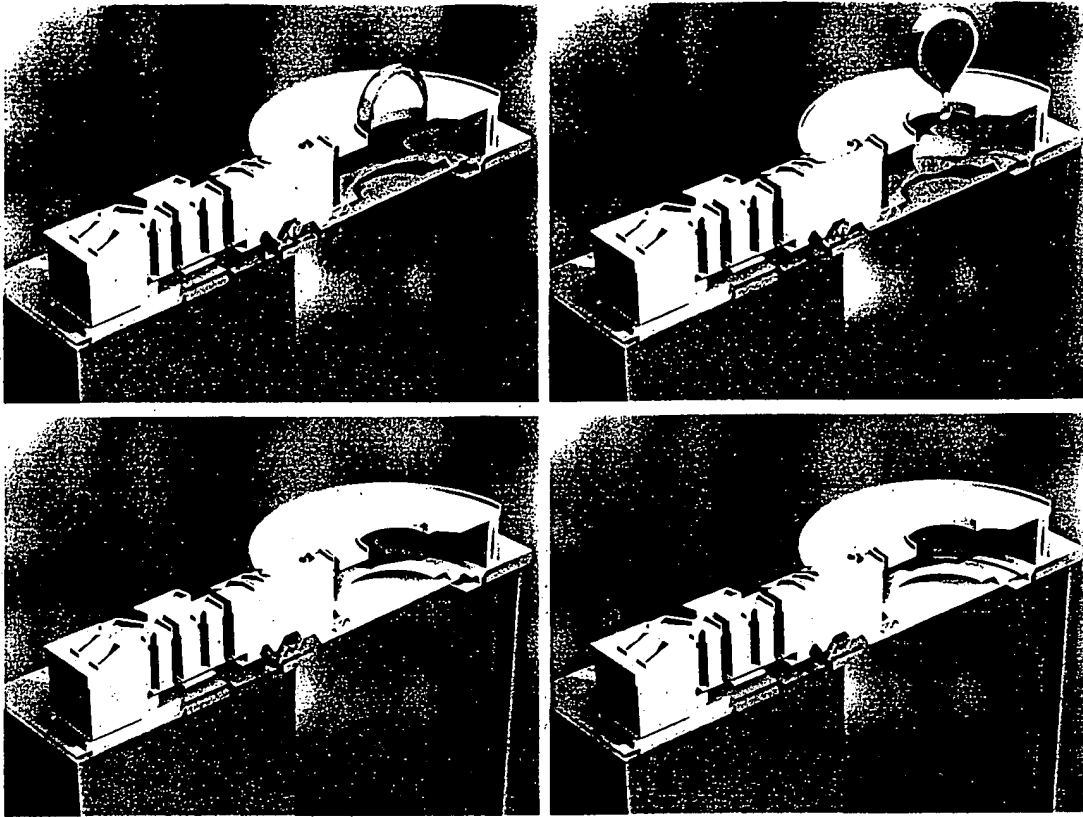
Glue the chip into a package with an ink inlet hole, for example, a pressure transducer package. The ink hose should include a 0.5 micron absolute filter to prevent contamination of the nozzles.

The prototype Memjet chips are 3 mm square, but the ink inlet hole region is only about 240 x 160 microns, in the center of the chip. Glue the chip into the package so that the chip ink inlet is over the hole in the package. This requires only 500 micron accuracy. Wire bond the 6 connections to nozzles to be tested.

Fill the packaged printhead under approx. 5 kPa ink pressure to prime it.



17) Test

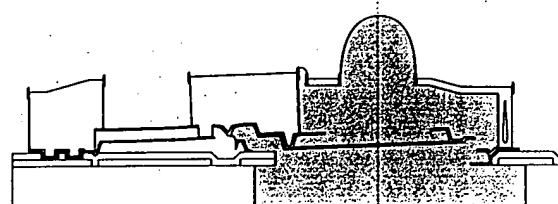


PROCESS DETAILS

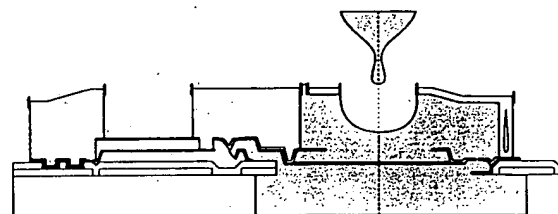
Testing of the inkjets is performed by a mixture of physical observation and simulation.

The primary physical test is to take high speed photomicrographs of the ink drops in flight. This is done with a special optical microscope, a high speed flash, a gated photomultiplier plate, and a high speed CCD camera. The images are stored on computer and carefully compared to the simulation results. When the simulation matches the experimental images to within a few percent, then the simulation can act as a 'microscope' able to see almost any aspect of the nozzle operation.

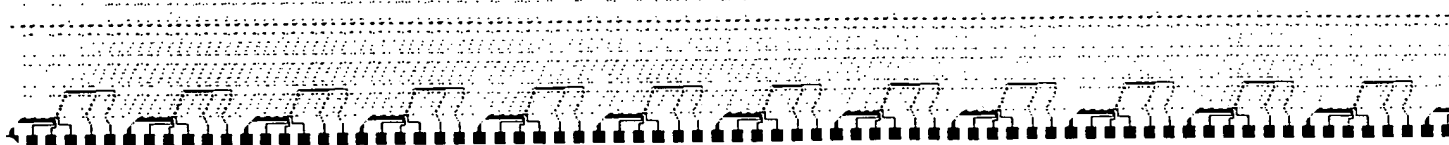
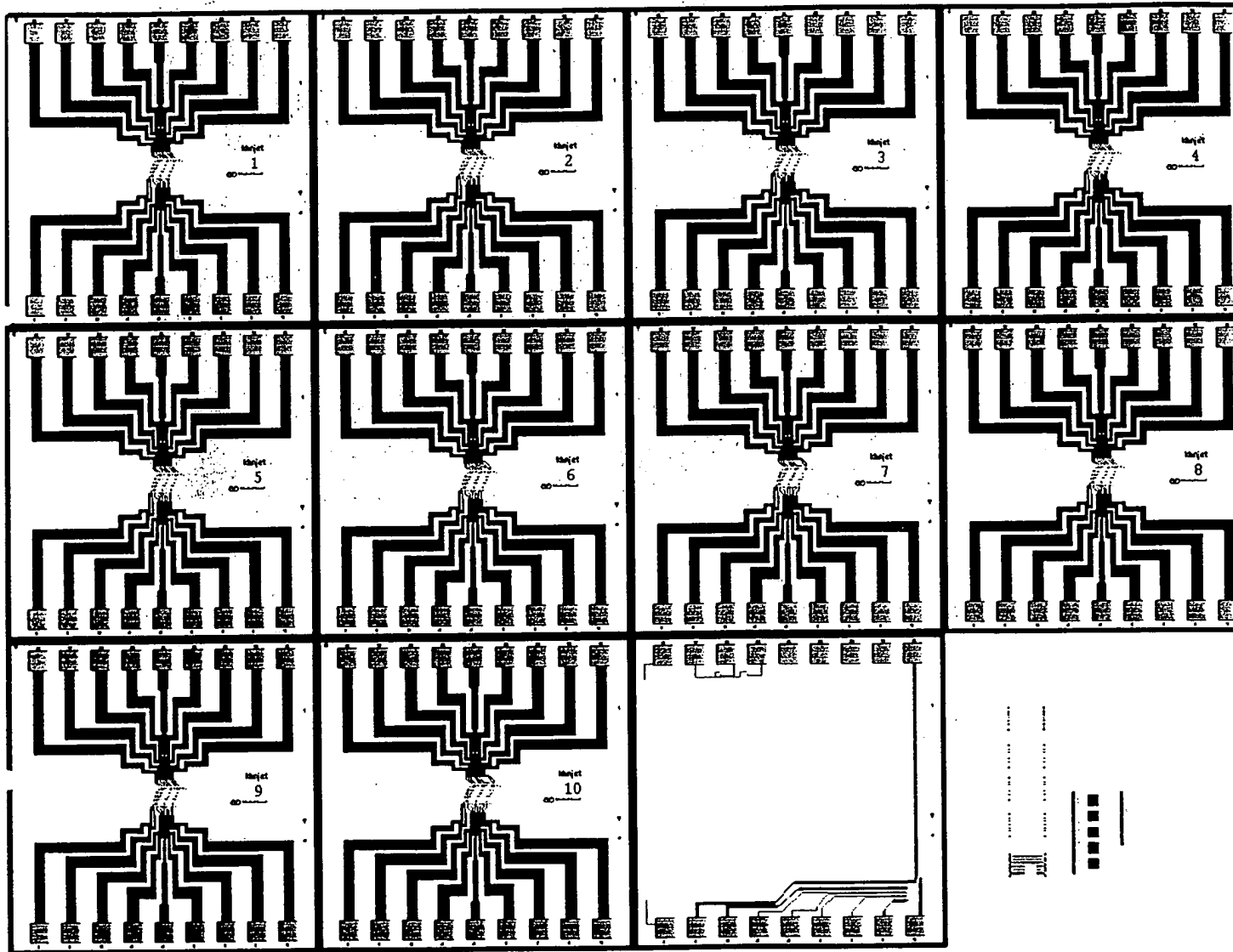
Silverbrook Research is establishing a testing laboratory that will be able to perform the necessary tests, and correlate these tests with extensive simulation results.



Actuate



Return



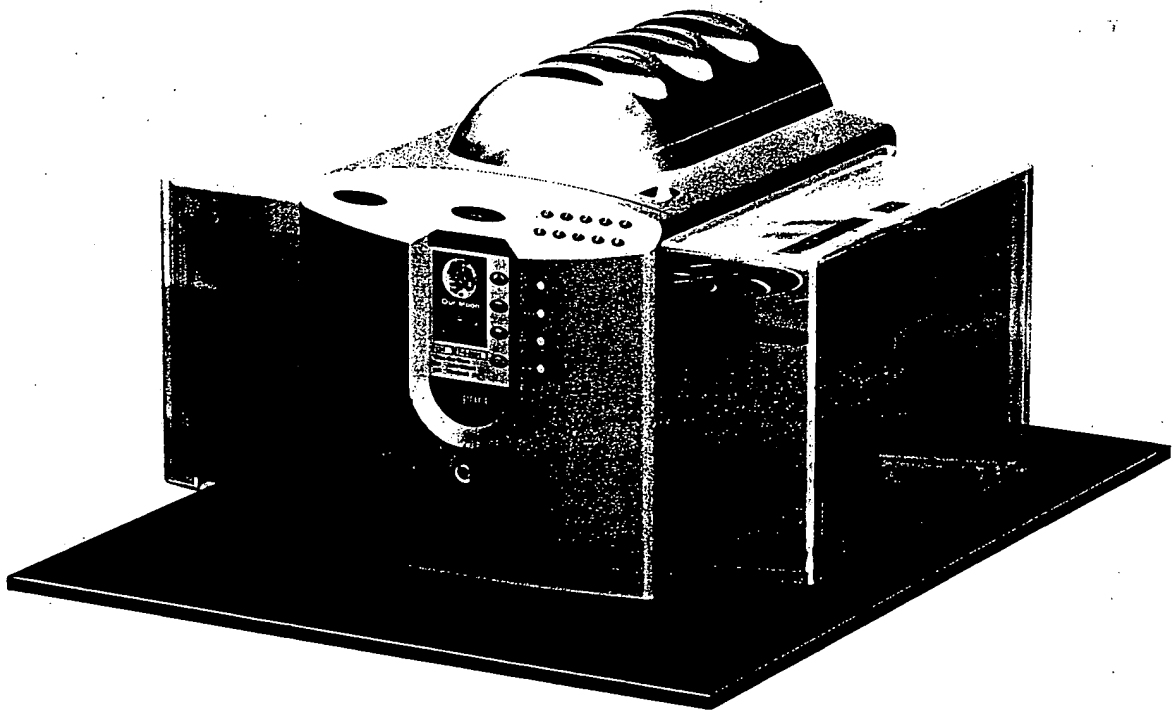
S-print Product Concept

DUPLEX NETWORK COLOR PRINTER

120 PPM

1600 DPI PHOTOGRAPHIC QUALITY

DRAFT VERSION 0.1, 20 APRIL 1999



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Fax: +61 2 9818 6711
Email: info@silverbrook.com.au

1 S-print Overview

S-print is a high-speed duplex network color printer intended for high-volume office use. It features 2000-sheet motorized paper trays, 120 page-per-minute operation, and 1600 dpi photographic-quality output.

With 20 times the speed of the best network color laser printers, and 4 times the speed of the best network monochrome laser printers, S-print effectively targets the \$40 billion desktop laser printer market¹. With its high performance and photographic-quality output, it also competes against offset printing for print runs smaller than 5000 copies.

S-print accommodates A4/Letter sized media and, with a tray adapter, A3/Tabloid sized media. It achieves simultaneous high quality and performance using full-color page-width 1600 dpi Memjet printheads.

S-print uses an embedded DSP-based raster image processor (RIP) to rasterize Postscript and PCL page descriptions at high speed. The standard RIP uses a single DSP, but up to three additional DSP modules can be plugged in to increase performance.

The RIP compresses and stores the rasterized page images on an internal high-capacity hard disk. While simple page descriptions are rasterized at the full 120 ppm printing rate, more complex page descriptions may take longer. Pre-rasterized documents retrieved from the internal hard disk are always printed at the full 120 ppm printing rate. Any document can be "printed" to the hard disk for later high-speed retrieval.

Users can walk up to an S-print, select locally-stored documents on its color LCD, and print them immediately, without ever going near a workstation. Documents printed in this way always print at the full 120 ppm rate. The standard 14GB internal hard disk stores over 6000 image-intensive pages. Because of its walk-up capability and high speed, S-print is likely to displace many uses of short-run offset printing.

S-print uses duplexed printheads for simultaneous double-sided printing. During the pilot phase of Memjet printhead manufacturing when the printhead defect density is still potentially high, each printhead is replicated to achieve 2:1 nozzle redundancy. This allows factory-detected defective nozzles to be bypassed, and so maximises printhead yield. A pair of custom print engines expand, dither and print page images to the duplexed printheads in real time.

Apart from custom print engines and Memjet printheads, S-print is built using standard off-the-shelf electronic components.

1. 1998 market size (source: IT Strategies)

2 Network Printer Comparison

Table 1 compares the specifications and running costs of S-print with those of various Hewlett-Packard network laser printers, ranging from the entry-level HP 4500 to the high-end HP 8500, and including the high-end monochrome HP 8100. Product descriptions for these HP printers appear at the end of this document (from www.hp.com).

Table 1. Network printer comparison

	S-print	HP 4500 ^a	HP 8500 ^a	HP 8100 ^a (monochrome)
Specifications				
Available	Projected 2001	Now	Now	Now
Speed (color)	120 ppm	4 ppm	6 ppm	NA
Speed (monochrome)	120 ppm	16 ppm	24 ppm	32 ppm
Technology	Liquid Inkjet	Laser EP	Laser EP	Laser EP
Dot pitch	1600 dpi	600 dpi	600 dpi	600 dpi
Configuration	Desktop	Desktop	Floor-standing	Desktop
Duty cycle (pages per month)	600,000	35,000	60,000	150,000
Duplex	Yes	Option	Option	Option
Full bleed (prints to edge of paper)	Yes	No	No	No
Electronic collation	Yes	Option	Option	Option
Walk-up printing of stored documents	Yes	No	No	Option
Paper path	Straight	Complex	Complex	Complex
Color model	CMYK	CMYK	CMYK	Monochrome
Colorant	Water-based ink	Dry toner	Dry toner	Dry toner
Network-ready	Yes	Option	Option	Option
Standard paper capacity	2000	400	1100	1100
Optional maximum paper capacity	2000	900	3100	3100
Maximum paper size	A3/Tabloid	A4/Letter	A3/Tabloid	A3/Tabloid
Raster image processor (RIP)	1-4 Parallel DSPs	133 MHz MIPS 4700	133 MHz MIPS 4700	166 MHz NEC VR4310
Memory (standard)	64 MB	32 MB	32 MB	16 MB
Memory (maximum)	256 MB	208 MB	256 MB	208 MB
Disk drive	14 GB	Optional 2.1 GB	Optional 2.1 GB	Optional 2.1 GB
Control panel	Color TFT LCD	2-line alpha LCD	2-line alpha LCD	2-line alpha LCD
Printer languages	Postscript, PCL	Postscript, PCL	Postscript, PCL	Postscript, PCL
Fonts	TrueType, Postscript	TrueType, Postscript	TrueType, Postscript	TrueType, Postscript
Warm-up time	Instant	5 minutes	5 minutes	1.5 minutes
Power consumption (color)	300 Watts	300 Watts	375 Watts	NA
Power consumption (monochrome)	75 Watts	500 Watts	750 Watts	700 Watts
Power consumption (standby)	2 Watts	140 Watts	220 Watts	145 Watts
Power consumption (15% coverage)	40 Watts	300 Watts	300 Watts	700 Watts
Dimensions (H x W x D, imperial)	13.4" x 20.5" x 14.6"	15.4" x 19.7" x 22.4"	41.7" x 26.3" x 28.1"	22.3" x 20.5" x 21.6"
Dimensions (H x W x D, metric)	340 x 520 x 370 mm	390 x 500 x 570 mm	1060 x 668 x 714 mm	566 x 520 x 540 mm
Weight	20 kg (44 lb)	50.8 kg (112 lb)	101.2 kg (223 lb)	54 kg (120 lb)
Printer cost				
Minimum system	\$3,000	\$2,499	\$5,999	\$2,679
Optioned system ^b	\$6,000	\$4,674	\$7,895	\$5,774
Consumables capacity				
Black ink/toner (5% coverage)	88,778 pages	9,000 pages	17,000 pages	20,000 pages

Table 1. Network printer comparison

	S-print	HP 4500 ^a	HP 8500 ^a	HP 8100 ^a (monochrome)
Color ink/toner (5% coverage)	44,389 pages	6,000 pages	8,500 pages	NA
Drum kit	NA	6,500 pages	12,500 pages	NA
Transfer kit	NA	25,000 pages	75,000 pages	NA
Fuser kit	NA	50,000 pages	100,000 pages	NA
Consumables cost				
Black ink/toner	\$100.00	\$77.94	\$136.00	\$273.00
Color ink/toner	\$150.00	\$97.51	\$190.00	NA
Drum kit	NA	\$75.04	\$187.00	NA
Transfer kit	NA	\$174.00	\$445.00	NA
Fuser kit	NA	\$203.00	\$360.00	NA
Cost per page (not including paper)				
Light (5% coverage)	1.13 cents	8.00 cents	9.96 cents	1.37 cents
Typical (15% coverage)	3.38 cents	19.48 cents	24.97 cents	4.10 cents
Full page photos	11.26 cents	59.67 cents	77.51 cents	13.65 cents
Annual consumables revenues ^c				
Pages printed	936,000	31,200	46,800	249,600
Revenue	\$31,629	\$6,078	\$11,685	\$10,221

a. All HP specifications and prices from www.hp.com, 13 April 1999.

b. Duplex, network-ready, 2000-sheet capacity, 64MB, (S-print: 4 DSPs).

c. If the printer is used for 1 hour per day, 5 days per week, at 15% coverage, with 50% RIP overhead. High-end users will likely exceed this, while the average will probably be lower.

The actual market in which S-print would compete is wider than the network color printer market, since Memjet-based printers can also undercut the cost-per-page of monochrome laser printers.

In the table, the S-print ink is priced to slightly undercut monochrome laser printers, and to undercut color laser printers by a factor of 6 to 8. Color laser consumables are complex, including toner, complex mechanical toner stirring, imaging drums, transfer systems, fusers, and various other accessories. It is therefore doubtful that the price of these consumables could be reduced by a similar factor and still be profitable.

S-print ink cartridges are highly profitable. The black ink cartridge contains 1 liter of ink, costs \$5 to manufacture, and sells for \$100. The color ink cartridge contains 0.5 liter of ink, costs \$3.50 to manufacture, and sells for \$150.

The S-print printer is priced between \$3000 and \$6000 depending on options. This makes it competitive with high-end monochrome laser printers such as the HP 8100. Just as color inkjet printers have displaced monochrome inkjet printers at the low end of the market, color is also likely to displace monochrome in the midrange once color matches or betters the speed and cost-per-page of monochrome.

In the annual consumables section at the end of the table, S-print is shown to print almost four times as many pages as the HP 8100. This is enabled by the fact that it prints four times faster than the HP 8100, and is justified by the likelihood that it will displace much short-run offset-printing in favor of in-house printing.

3 Utilization of Pilot Phase Yield

Printhead manufacturing volume is predicted to go through three major phases:

- 1) An initial lab phase, where only around 100 wafers per month are processed, the yields are low to non-existent, and the available number of printheads is very limited. Defect densities above 100 per cm^2 are assumed.
- 2) A pilot phase, where the number of wafers processed each month is around 5000. Defect densities are assumed to be between 10 per cm^2 and 100 per cm^2 , necessitating the use of redundancy to achieve good printhead yields.
- 3) A full manufacturing phase, where 25,000 wafers are processed each month. Here defect densities are expected to fall from around 8 per cm^2 to 0.1 per cm^2 over the course of five years. During this phase, it is most cost-effective to *not* use printhead redundancy.

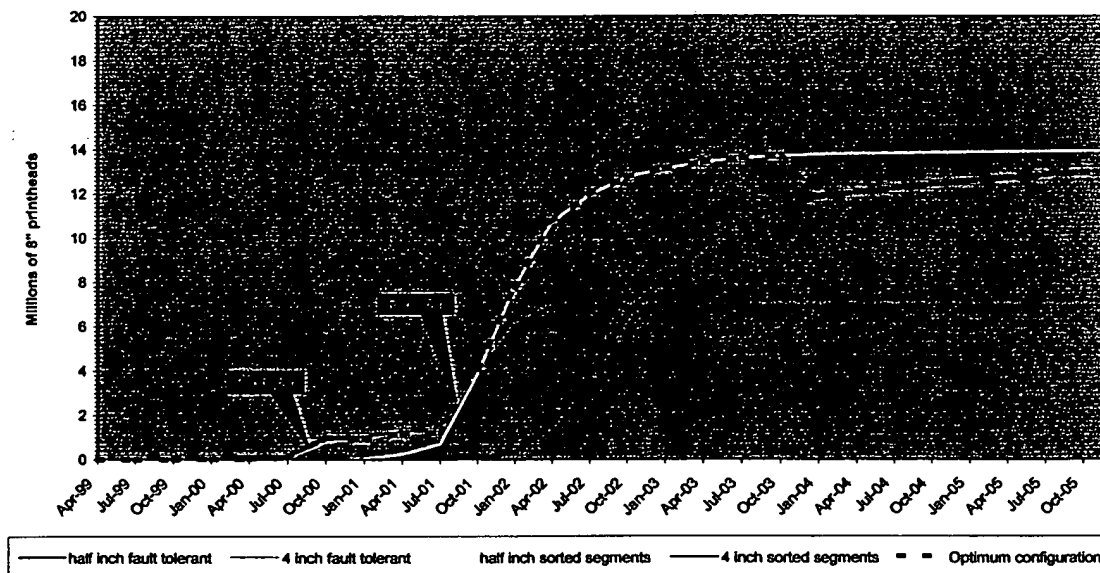


Figure 1. Millions of 8" printheads per quarter for various configurations (showing the optimum configuration)

Figure 1 shows manufacturing volume as a function of printhead configuration. The pilot phase, from October 2000 to October 2001, is characterized by a manufacturing volume of about one million deployable 8" printheads, made possible by redundant-nozzle printhead configurations. The full manufacturing phase, starting in October 2001, is characterized by a rapidly increasing manufacturing volume no longer reliant on nozzle redundancy.

The market focus during the pilot phase and the full manufacturing phase should be different. During the pilot phase, markets which are relatively insensitive to printhead cost should be targeted. These include:

- 1) Wide-format printing (machine prices around \$10,000)
- 2) Network color printing (machine prices between \$3000 and \$7000)

3) Digital commercial printing (machine prices \$100,000 and up)

4) Photo finishing (machine prices between \$5000 and \$20,000)

During the full manufacturing phase, high volume markets can also be targeted.

One million redundantly-deployable 8" printheads is sufficient for around 167,000 S-print printers.

Table 2 indicates the size of the various digital printing markets. Markets in which S-print is likely to compete effectively are highlit.

Table 2. Selected digital printing markets, 1998 (source: IT Strategies)

	Total value	Printers	Media (paper etc.)	Ink or other colorants	1998 unit shipments	Installed base
Workplace & SOHO (high end)	\$10,000 M	\$10,000 M	\$10,000 M	\$10,000 M	4,000,000	85,000,000
Consumer & SOHO Ink Jet	\$17,800 M	\$9,000 M	\$3,520 M	\$5,280 M	29,000,000	81,000,000
Fax/MFP	\$8,000 M	\$4,000 M	\$1,500 M	\$2,500 M	5,000,000	12,500,000
Color Copier	\$5,750 M	\$2,000 M	\$750 M	\$3,000 M	45,000	183,000
Wide Format Graphic	\$2,930 M	\$500 M	\$1,080 M	\$1,350 M	44,000	84,000
Wide Format CAD	\$1,733 M	\$450 M	\$513 M	\$770 M	125,000	500,000
Bar Code/Direct Mail/Coding	\$1,150 M	\$750 M	\$100 M	\$300 M	14,000	75,000
Workplace & SOHO (low end)	\$10,000 M	\$10,000 M	\$10,000 M	\$10,000 M	4,000,000	85,000,000
Workplace & SOHO (mid end)	\$10,000 M	\$10,000 M	\$10,000 M	\$10,000 M	4,000,000	85,000,000
Kiosk Photo Printing	\$241 M	\$120 M	\$48 M	\$73 M	10,000	36,000
Card Printing (ID, Smart Cards)	\$300 M	\$101 M	\$109 M	\$90 M	18,000	51,000
Proofing Printing	\$513 M	\$250 M	\$105 M	\$158 M	11,000	72,000
MICR Printing	\$205 M	\$90 M	\$50 M	\$65 M	15,000	50,000
Medical Printing (X-ray, diagnostic)	\$125 M	\$35 M	\$50 M	\$40 M	3,000	15,000
Forms Printing	\$110 M	\$50 M	\$20 M	\$40 M	500	1,500
Label Printing	\$13 M	\$10 M	\$2 M	\$1 M	15,000	16,000
Total	\$82,520 M	\$34,251 M	\$18,777 M	\$29,492 M	42,820,500	134,083,500

a. S-print competes at the high end of this market, where the unit price of a printer is above \$2000.

4 Printer Mechanics

S-print is compact, with minimum dimensions of 13.4" (340 mm) high by 20.5" (521 mm) wide by 14.6" (371 mm) deep (see Figure 2). As the print engine is small, the machine is dominated by paper and ink storage.

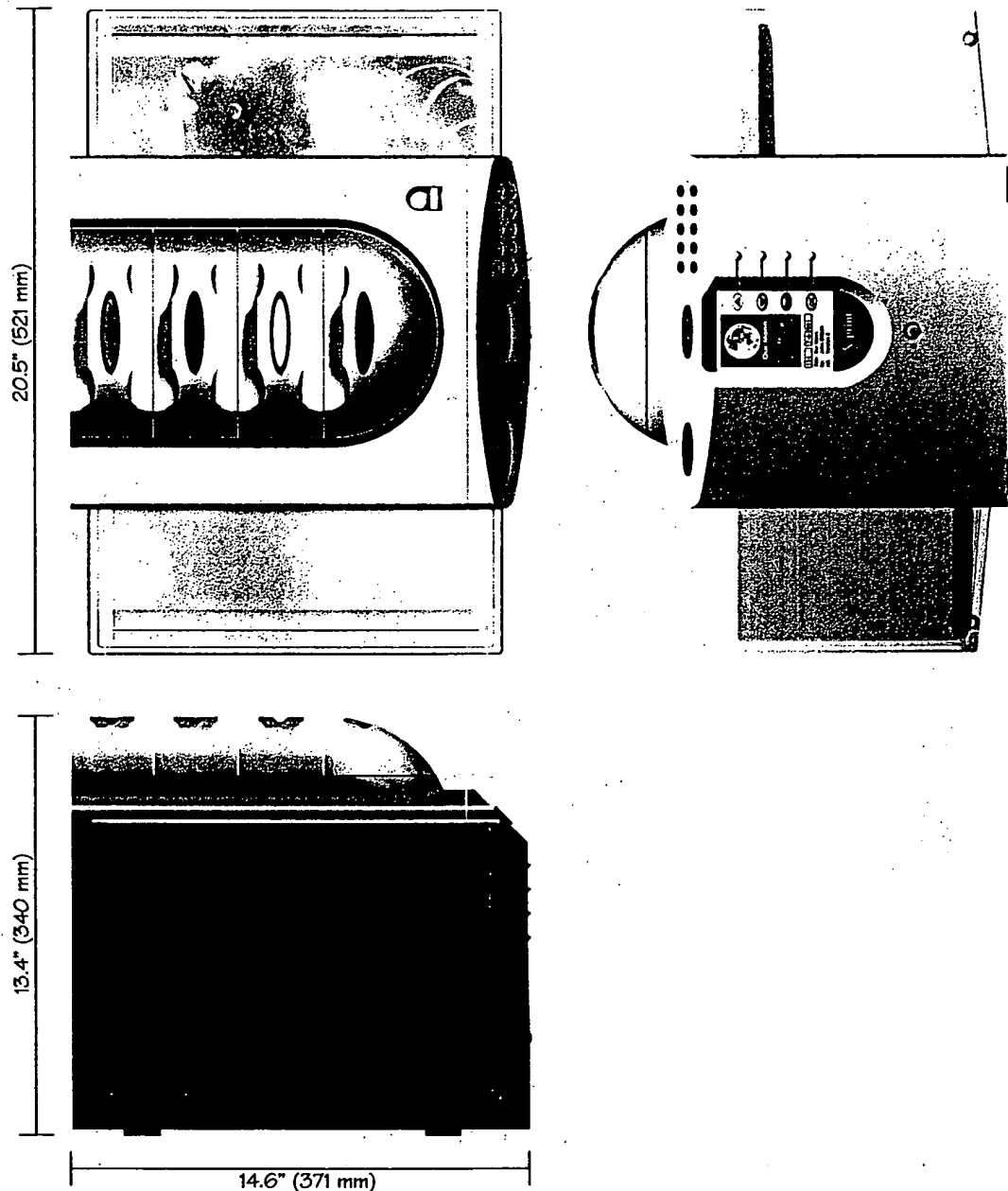


Figure 2. Plan and elevations of S-print printer unit

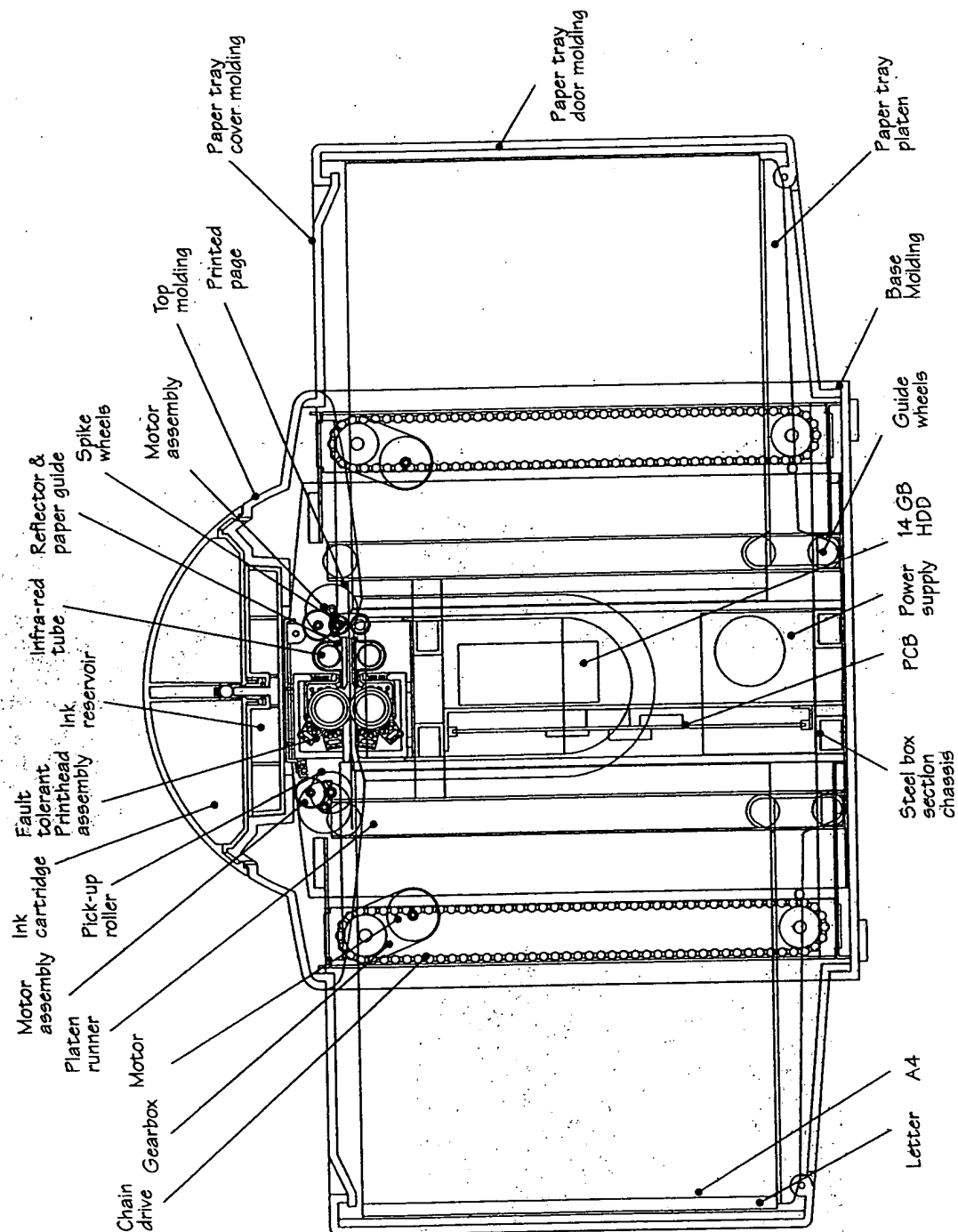


Figure 3. Front elevation of S-print (rotated)

The overall views of S-print are shown in Figure 3 and Figure 4. The elevation in Figure 3 shows the basic structure of the printer. It is built around a steel box section chassis with metal front, back and base panels attached. Two motorized paper trays form the basic paper path, with the imaging engines in the middle. The printer prints the wide edge of the paper to enable A3/Tabloid printing, and to achieve a compact form factor.

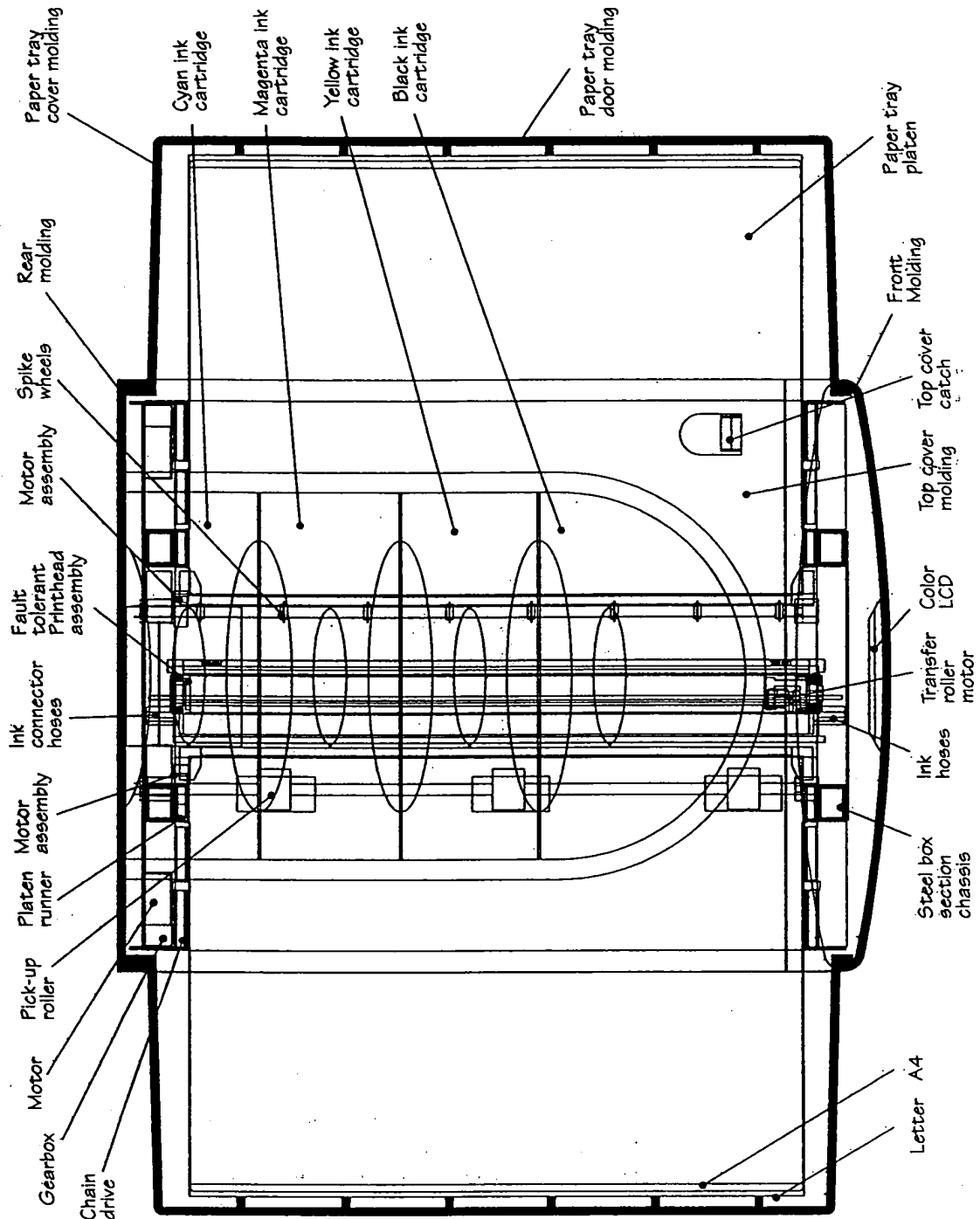


Figure 4. Plan of S-print

The trays comprise a metal platen with rollers, roller guides, a chain drive, motor and high ratio gearbox. The chain drive is duplicated on the opposite side of the platen and linked via an axle at base level. This is a proven mechanism that allows smooth lifting and lowering of up to 2000 sheets of paper. A metal plate on one side of the paper tray can be relocated to provide either A4 or Letter width guidance. This entire paper tray assembly is duplicated on the other side of the printer to accept the high speed paper flow. Each tray is

housed in an injection-molded, color-tinted, transparent housing with a hinged door and latch sensors.

Another motor assembly powers the paper pick-up roller which feeds the sheet through to the imaging engines. The top molding in Figure 5 can be unlatched and hinged upwards to reveal the metalwork chassis for the upper imaging engine. This in turn can be unlocked and pivoted upward for access to the printheads and drying lamps.

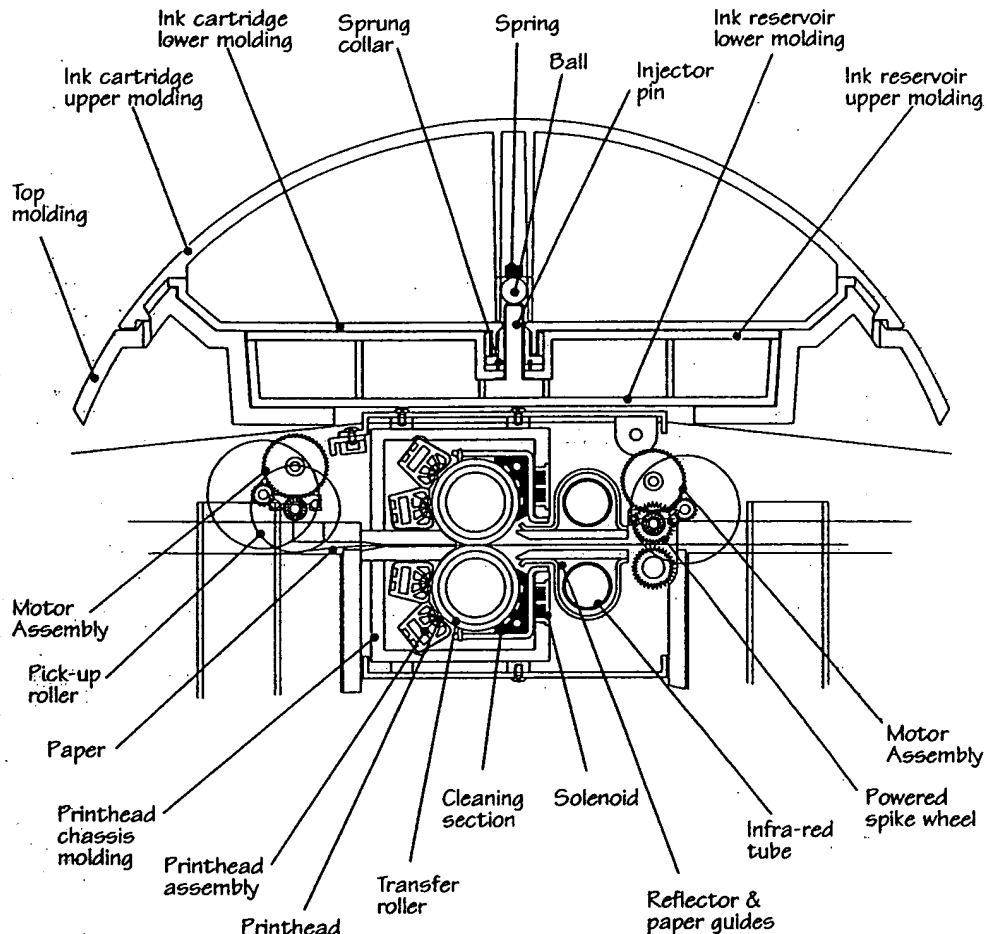


Figure 5. Ink supply and paper path between duplexed imaging engines

Figure 5 shows the workings of S-print. The straight paper path allows the paper to be fed at high speed past the printheads. The two imaging engines are mounted together in an adjustable assembly. The top imaging engine can pivot upwards to allow access to paper jams and to the lower imaging engine and infra-red drying lamps.

The transfer roller caps the printheads whenever S-print is not printing. Whenever a page is to be printed, the solenoid is activated, and the roller pivots away from the printheads and contacts against the transfer roller from the other imaging engine providing traction onto the paper.

The paper then passes the infra-red tubes which dry the ink before a set of spike wheels eject the printed page into the exit tray.

The ink cartridges snap fit onto the top molding. Ink is automatically fed via a sprung colored pin into a permanent ink reservoir. The reservoir serves to provide an early warning to replace the ink cartridge and makes the contact with the embedded QA cartridge chip. The provision of a large reservoir means that the ink cartridges typically only need to be replaced when all four colors are empty, rather than when the first color is empty. Each ink color reservoir connects via hoses to the printhead extrusion assemblies, which are daisy chained together via flexible hose connections (Figure 4).

The main PCB, power supply and 14GB hard disk are shown in Figure 3. Access to these components is via the front and rear moldings.



Figure 6. Front panel user interface

Figure 6 shows the color LCD interface with four changeable function buttons for navigating the user interface. The LCD displays a preview of the front page of the document to be printed. The keypad on the front molding allows the desired number of copies to be entered. Documents to be printed locally can also be selected by an ID number using the keypad. This can be quicker than scrolling through stored documents if there are many.

4.1 IMAGING ENGINES

S-print uses duplexed imaging engines (Figure 7) for simultaneous double-sided printing. During the pilot phase of manufacturing when the printhead defect density is still potentially high, each printhead is replicated to achieve 2:1 nozzle redundancy. This allows factory-detected defective nozzles to be bypassed, and so maximises printhead yield.

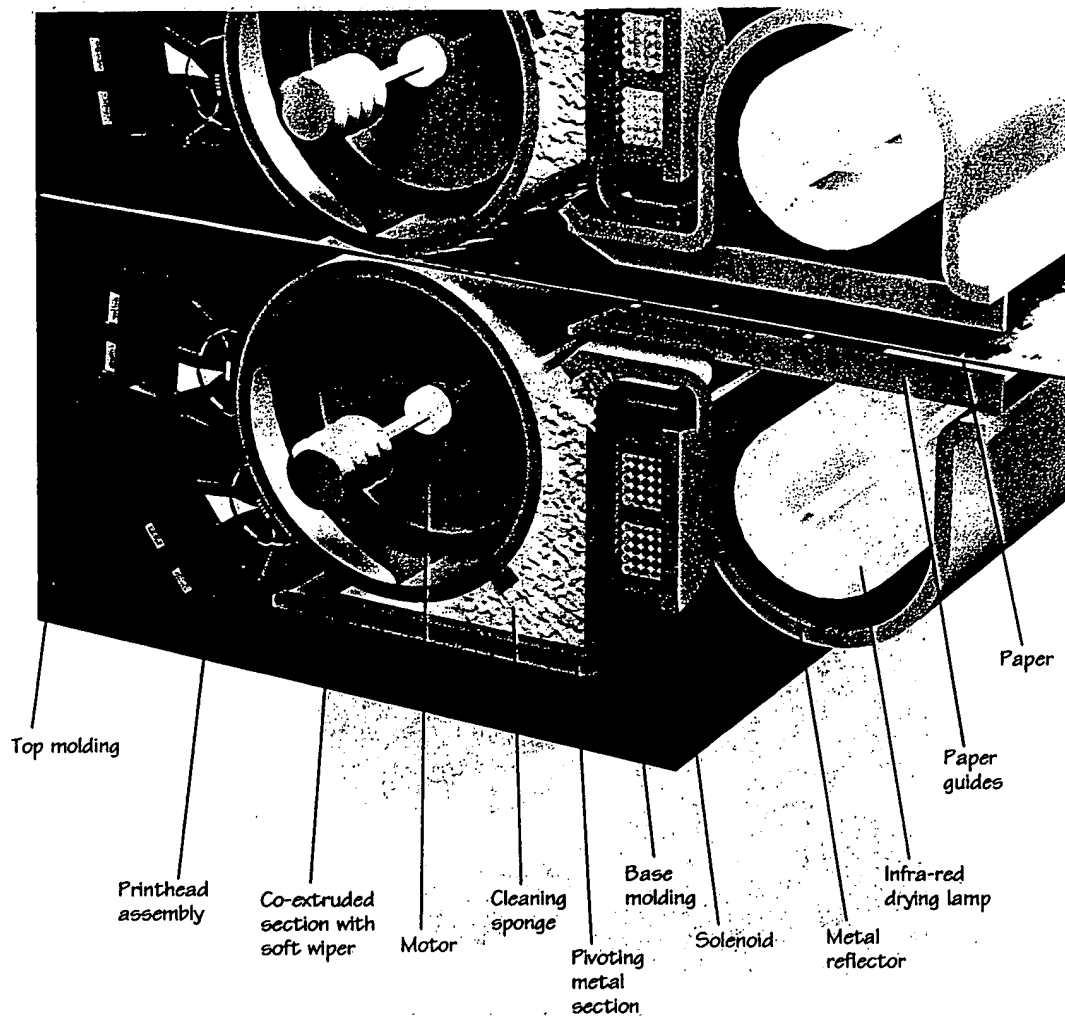


Figure 7. Duplexed imaging engines and drying lamps

Each imaging engine therefore contains two printhead assemblies (Figure 8) mounted side-by-side, sharing the same powered transfer roller and cleaning station.

The four printhead assemblies in the two imaging engines share the same ink supply.

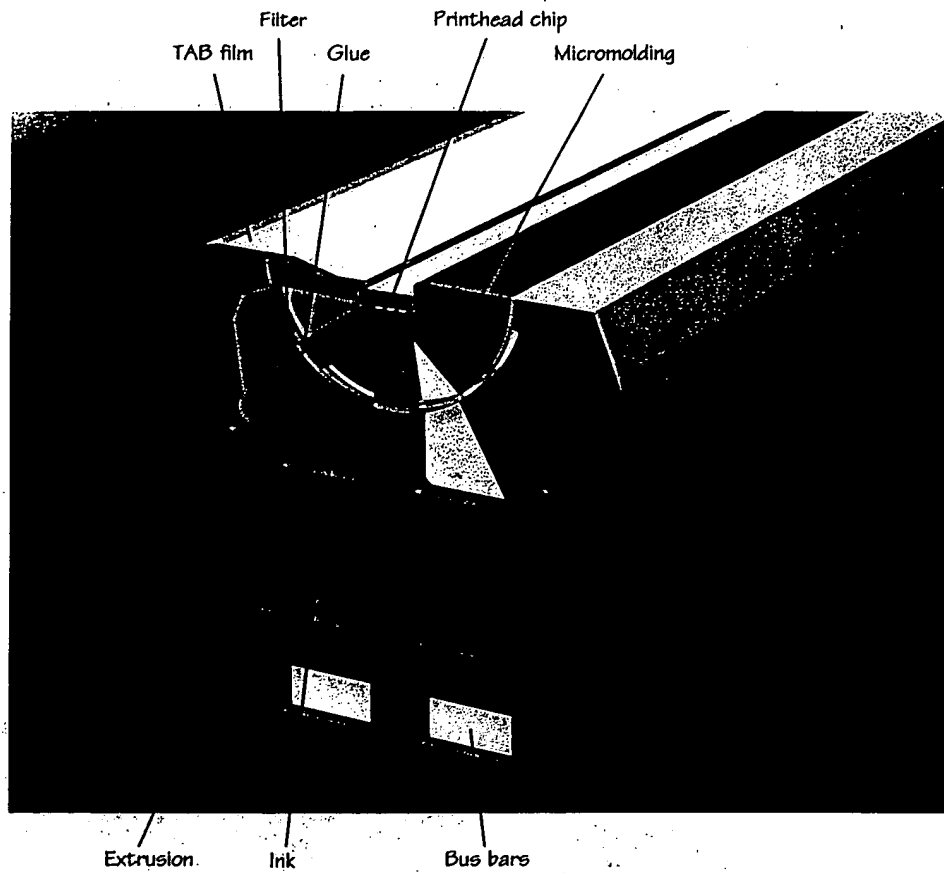


Figure 8. Cross-section of printhead assembly

5 Ink Cartridge

The black cartridge holds 1 liter (33.8 fluid ounces¹), while the cyan, magenta and yellow cartridges each hold half a liter. The cartridges plug directly into the top of the printer and are comprised of two main moldings ultrasonically welded together with a QA chip in the lower molding (Figure 9).

The upper molding houses a sprung ball-bearing that is held captive against the inner molding. This provides the main seal to the cartridge with a secondary hydrophobic elastomeric seal to the entry port on the lower molding.

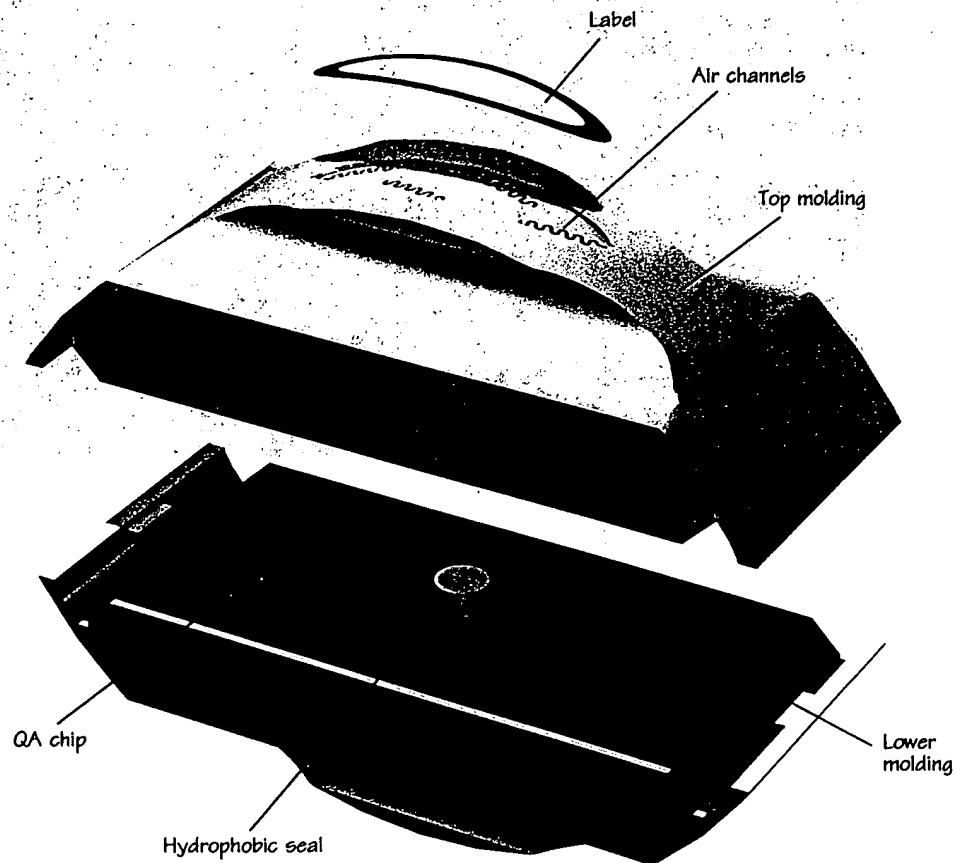


Figure 9. Ink cartridge explosion

The cartridge connects to the printheads via the printer ink reservoir. This has a hollow pin that emerges from a sprung sleeve when the cartridge is pushed on. The pin pushes the ball bearing back and allows ink to flow. Tortuous hydrophobic air channels are provided at the top of the unit under the label. The four ink cartridges are differently keyed by plastic protrusions to prevent any incorrect insertion or orientation of the units.

1. 2.11 US pints, 1.76 British pints, or 0.0042 hogsheads.

6 Memjet-Based Printing

A Memjet printhead produces 1600 dpi bi-level CMYK. On low-diffusion paper, each ejected drop forms an almost perfectly circular 22.5µm diameter dot. Dots are easily produced in isolation, allowing dispersed-dot dithering to be exploited to its fullest. Since the Memjet printhead is the width of the page and operates with a constant paper velocity, the four color planes are printed in perfect registration, allowing ideal dot-on-dot printing. Since there is consequently no spatial interaction between color planes, the same dither matrix is used for each color plane. Dot-on-dot printing minimizes 'muddying' of mid-tones caused by inter-color bleed.

A page layout may contain a mixture of images, graphics and text. Continuous-tone (contone) images and graphics are reproduced using a stochastic dispersed-dot dither. Unlike a clustered-dot (or amplitude-modulated) dither, a *dispersed-dot* (or frequency-modulated) dither reproduces high spatial frequencies (i.e. image detail) almost to the limits of the dot resolution, while simultaneously reproducing lower spatial frequencies to their full color depth, when spatially integrated by the eye. A *stochastic* dither matrix is carefully designed to be free of objectionable low-frequency patterns when tiled across the image. As such its size typically exceeds the minimum size required to support a particular number of intensity levels (e.g. 16×16×8 bits for 257 intensity levels). S-print uses a dither *volume* of size 64×64×3×8 bits. The volume provides an extra degree of freedom during the design of the dither by allowing a dot to change states multiple times through the intensity range (rather than just once as in a conventional dither matrix).

Human contrast sensitivity peaks at a spatial frequency of about 3 cycles per degree of visual field and then falls off logarithmically, decreasing by a factor of 100 beyond about 40 cycles per degree and becoming immeasurable beyond 60 cycles per degree. At a normal viewing distance of 12 inches (about 300mm), this translates roughly to 200-300 cycles per inch (cpi) on the printed page, or 400-600 samples per inch according to Nyquist's theorem.

In practice, contone resolution above about 300 ppi is of limited utility outside special applications such as medical imaging. Offset printing of magazines, for example, uses contone resolutions in the range 150 to 300 ppi. Higher resolutions contribute slightly to color error through the dither.

Black text and graphics are reproduced directly using bi-level black dots, and are therefore not antialiased (i.e. low-pass filtered) before being printed. Text is therefore *supersampled* beyond the perceptual limits discussed above, to produce smoother edges when spatially integrated by the eye. Text resolution up to about 1200 dpi continues to contribute to perceived text sharpness (assuming low-diffusion paper, of course).

S-print uses a contone resolution of 320 ppi (i.e. 1600÷5), and a black text and graphics resolution of 1600 dpi.

7 Document Data Flow

Document transmission and document rasterization are decoupled to shield the user from interactions between the size and complexity of the document, and the memory capacity and RIP performance of S-print. This is achieved by storing each document's PDL file on the internal hard disk.

Because of the high resolution of the Memjet printhead, each page must be printed at a constant speed to avoid creating visible artifacts. This means that the printing can't be varied to match the input data rate. Document rasterization and document printing are therefore decoupled to ensure the printhead has a constant supply of data. A page is never printed until it is fully rasterized. This is achieved by storing a compressed version of each rasterized page image on the internal hard disk.

This decoupling also allows the RIP to run ahead of the printer when rasterizing simple pages, buying time to rasterize more complex pages.

The user indicates whether a document is to be stored permanently on the hard disk, printed, or both. So long as there is disk space available, the pages of transient documents are also cached on the disk until printed. This is particularly efficient when multiple copies of complex documents are being printed. This so-called electronic collation also obviates the need for an external collating mechanism, since each copy of a document is printed in its entirety before the next copy.

Because contone color images are reproduced by stochastic dithering, but black text and line graphics are reproduced directly using black dots, the compressed page image format contains a separate foreground bi-level black layer and background contone color layer. The black layer is composited over the contone layer after the contone layer is dithered.

Figure 10 shows the flow of a S-print document from network to printed page.

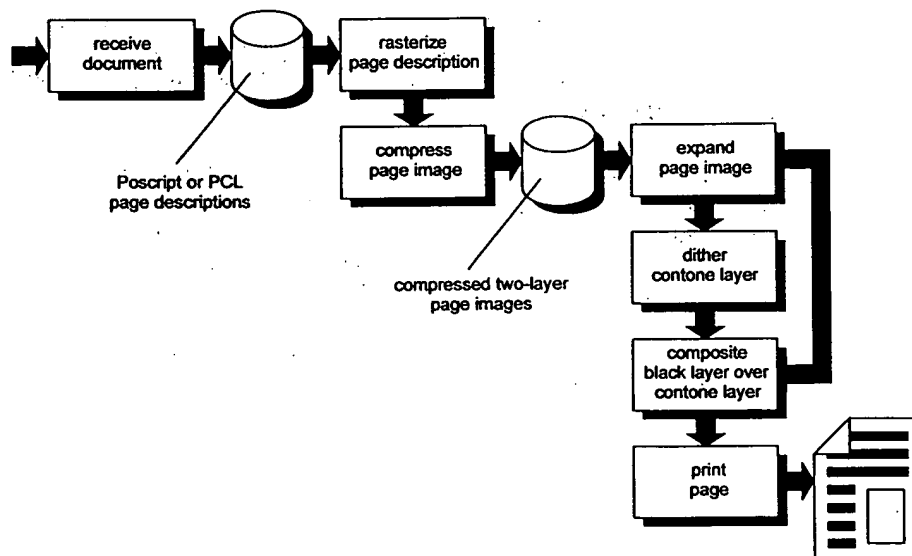


Figure 10. S-print document data flow

At 320 ppi, an A4/Letter page¹ of contone CMYK data has a size of 38MB. Using lossy contone compression algorithms such as JPEG, contone images compress with a ratio up to 10:1 without noticeable loss of quality, giving a compressed page size of 3.8MB.

At 1600 dpi, an A4/Letter page of bi-level data has a size of 30MB. Coherent data such as text compresses very well. Using lossless bi-level compression algorithms such as Group 4 Facsimile, ten-point text compresses with a ratio of about 20:1, giving a compressed page size of 1.5MB.

Once dithered, a page of CMYK contone image data consists of 120MB of bi-level data. Using lossless bi-level compression algorithms on this data is pointless precisely because the optimal dither is stochastic - i.e. since it introduces hard-to-compress disorder.

The two-layer compressed page image format therefore exploits the relative strengths of lossy JPEG contone image compression and lossless bi-level text compression. The format is compact enough to be storage-efficient, and simple enough to allow straightforward realtime expansion during printing.

Since text and images normally don't overlap, the normal worst-case page image size is 3.8MB (i.e. image-only), while the normal best-case page image size is 1.5MB (i.e. text-only). The absolute worst-case page image size is 5.3MB (i.e. text over image). Assuming a third of an average page contains images, the average page image size is 2.3MB. The standard 14GB internal hard disk therefore holds over 6000 such pages.

1. An A4/Letter page has a maximum area of 8.3"x11.7" (i.e. A4).

8 Printer Controller Architecture

The S-print printer controller consists of a controlling processor, various peripheral controllers, a raster image processor (RIP) DSP farm, and duplexed page expansion processors. These components are discrete and communicate via a shared bus and a shared 64MB memory, as illustrated in Figure 11.

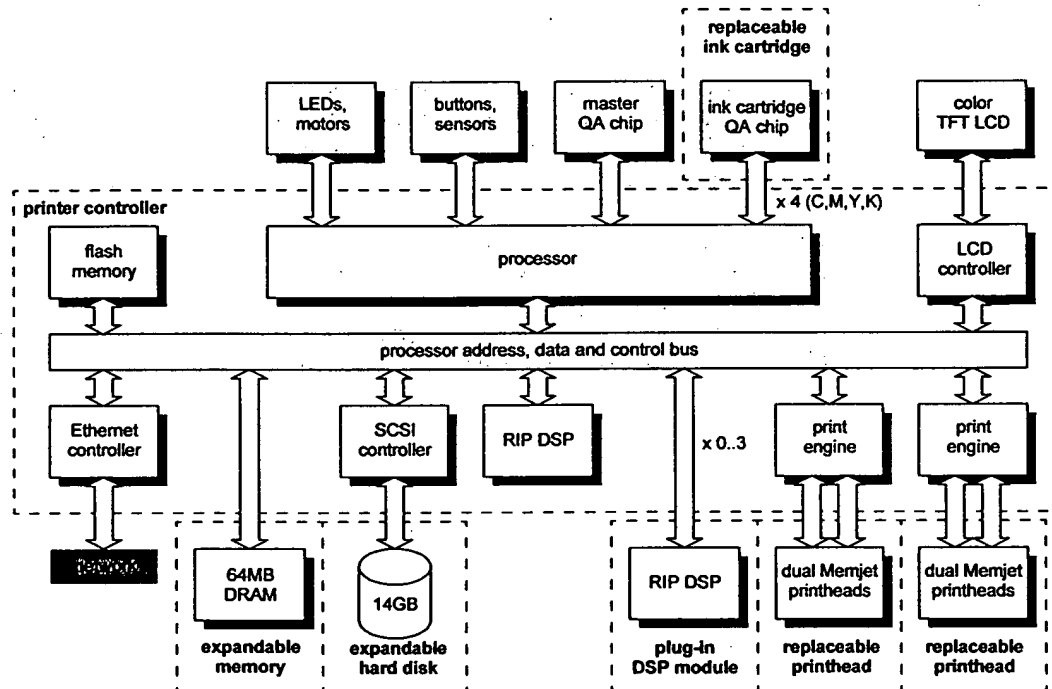


Figure 11. Printer controller architecture

The controlling processor handles communication with the network, controls the internal hard disk, controls the user interface (LCD, buttons and LEDs), controls the paper transport, handles ink cartridge authentication and ink monitoring, and feeds and synchronizes the RIP and the imaging engines. It consists of a medium-performance general-purpose microprocessor. Its associated peripheral controllers include a 10/100Base-T Ethernet controller, a SCSI disk controller, and a color TFT LCD controller. Optional controllers include an IEEE 1394 (Firewire) controller and a USB 2.0 controller for high-speed point-to-point communication with a workstation or server.

The RIP DSP farm rasterizes and compresses page descriptions to S-print's compressed page format. The DSP farm consists of between one and four general-purpose high-performance DSPs. Each additional DSP comes as a field-installable plug-in module.

Each print engines expands, dithers and prints page images to its associated replicated printhead in real time (i.e. at 60 ppm). The duplexed print engines print both sides of the page simultaneously (i.e. at 120 ppm).

The printer controller's flash memory holds the software for both the processor and the DSPs. This is copied to main memory at boot time. The flash memory also holds the defect characterization vectors for the two replicated printheads. These are copied to the print engines at boot time.

8.1 DETAILED DOCUMENT DATA FLOW

Document printing proceeds as follows.

The main processor receives the document's PDL file and stores it on the internal hard disk. It then runs the appropriate RIP software on the DSPs.

The DSPs rasterize each page description and compress the rasterized page image. The main processor stores each compressed page image on the hard disk. The simplest way to load-balance multiple DSPs is to let each DSP rasterize a separate page. The DSPs can always be kept busy since an arbitrary number of rasterized pages can, in general, be stored on the internal hard disk. This strategy can lead to poor DSP utilization, however, when rasterizing short documents.

The main processor passes back-to-back page images to the duplexed print engines. Each print engine stores the compressed page image into its local memory, and starts the page expansion and printing pipeline. Page expansion and printing is pipelined because it is impractical to store a 120MB bi-level CMYK image in memory.

The first stage of the pipeline expands the JPEG-compressed contone CMYK layer. The second stage, in parallel with the first, expands the Group 4 Fax-compressed bi-level black layer. The third stage dithers the contone CMYK layer, and composites the bi-level black layer over the resulting bi-level CMYK layer. The fourth stage prints the bi-level CMYK data via the printhead interface which controls the Memjet printhead.

The main processor streams compressed page images from the hard disk to the print engines at the required 120 ppm rate (i.e. 4.6MB/s on average, or 10.6MB/s worst-case).

Table 3. Print engine page image and FIFO data flow

PROCESS	input stream	input image	output image	output stream	input FIFO	output FIFO
receive contone	-	-	JPEG stream	1	-	3.8MB/s (10Mp/s)
receive bi-level	-	-	G4Fax stream	1	-	1.5MB/s (250Mp/s)
expand contone	JPEG stream	-	32-bit CMYK	8	3.8MB/s (10Mp/s)	38MB/s (10Mp/s)
expand bi-level	G4Fax stream	-	1-bit K	1	1.5MB/s (250Mp/s)	30MB/s (250Mp/s)
dither	32-bit CMYK	1	-	-	38MB/s (10Mp/s ^b)	-
composite	1-bit K	1	4-bit CMYK	1	30MB/s (250Mp/s)	120MB/s (250Mp/s)
print	4-bit CMYK	24, 1 ^c	-	-	120MB/s (250Mp/s)	-
					193MB/s	193MB/s
					387MB/s	

- a. dither combines with composite, so there is no external data flow between them
- b. 320 ppi \Rightarrow 1600 dpi (5 \times 5 expansion).
- c. Needs a window of 24 lines, but only advances 1 line.

The print engine data flow is summarized in Table 3. The aggregate traffic to/from memory is 387MB/s, all but 5.3MB/s of which relates to the FIFOs.

Each stage communicates with the next via a FIFO. Each FIFO is organized into lines, and the minimum size (in lines) of each FIFO is designed to accommodate the output window (in lines) of the producer and the input window (in lines) of the consumer. The inter-stage memory FIFOs are described in Table 4.

Table 4. Print engine local memory FIFOs

FIFO	format and line size	number of lines	FIFO size
contone CMYK	32-bit interleaved CMYK (267 ppi \times 11.7" \times 32 = 12.2KB)	8 \times 2 = 16	195KB
bi-level K	1-bit K (1600 dpi \times 11.7" \times 1 = 2.3B)	1 \times 2 = 2	5KB
bi-level CMYK	4-bit planar odd/even CMYK (1600 dpi \times 11.7" \times 4 = 9.1KB)	24 + 1 = 25	229KB
			429KB

8.2 PRINT ENGINE ARCHITECTURE

The print engine is implemented as a single custom chip. It shares a common design with print engines used in other Memjet printers.

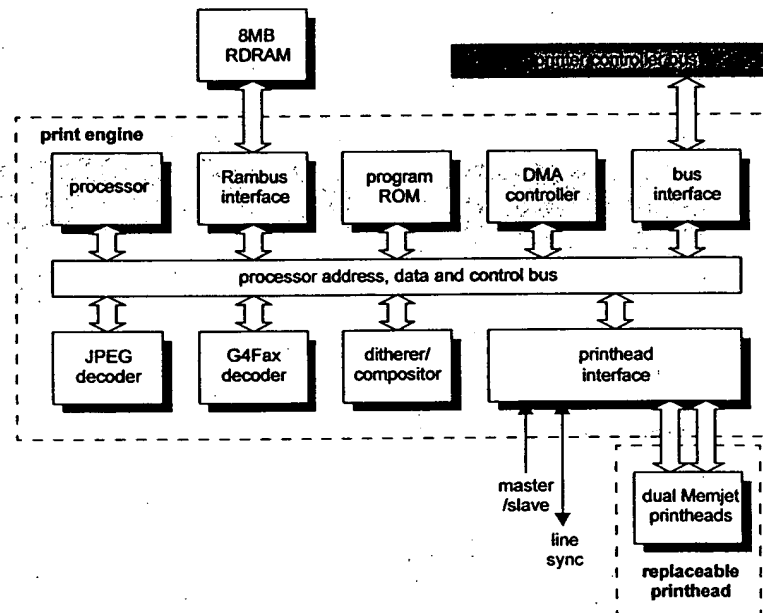


Figure 12. Shared-memory print engine architecture

There are two architectural variants of the print engine. The shared-memory version uses a local off-chip RDRAM to support the aggregate memory bandwidth required by page expansion and printing (see Figure 12). The pipelined version uses dedicated on-chip FIFOs (see Figure).

The shared-memory print engine consists of a general-purpose processor, a high-speed Rambus interface to the off-chip RDRAM, a small program ROM, a DMA controller, and an interface to the printer controller bus.

Both print engine's page expansion and printing pipeline consists of a standard JPEG decoder, a standard Group 4 Fax decoder, a custom ditherer/compositor unit, and a custom interface to the Memjet printheads. These are described in detail in design documents.

In the shared-memory version, the FIFOs are located in the dedicated off-chip RDRAM, and all inter-stage communication is controlled by the local processor via DMA. In the pipelined version, the FIFOs are on-chip, and the stages are self-synchronizing.

In the shared-memory version, the decoders obtain page data from the main processor via the local memory. In the pipelined version, the decoders obtain page data directly from the main processor over the printer controller bus.

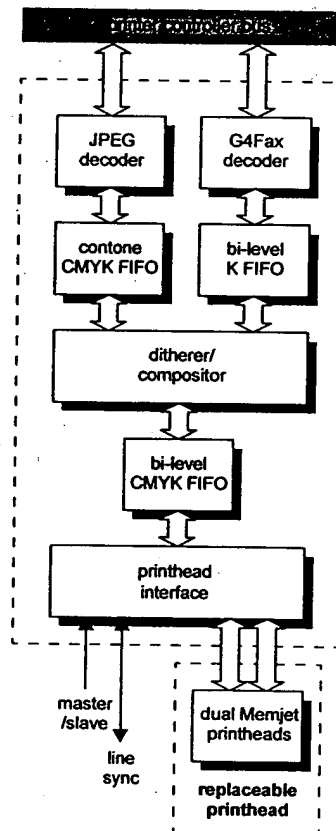


Figure 13. Pipelined print engine architecture

When several print engines are used in unison, such as in a duplexed configuration, they are synchronized via a shared line sync signal. Only one print engine, selected via the external master/slave pin, generates the line sync signal onto the shared line.

8.3 PRINTHEAD TIMING

Each print engine prints an A4/Letter page in one second. Since S-print uses a 12" print-head to print the long dimension of the page (11.7"), the printhead needs to traverse the short dimension of the page (8.5") in one second. At 1600 dpi, this equates to a 13.6KHz line rate. This is well within the operating frequency of the Memjet printhead, which in the current design exceeds 30KHz.

8.4 PRINTHEAD CHARACTERIZATION

Each redundant 12" printhead contains two complete 12" printheads, i.e. 76,800 nozzle pairs, characterized and matched so that no paired nozzles are both defective.

Printhead defects are either characterized and matched one segment at a time, or after the entire printhead has been built. In the former case nozzles are tested before integration with the ink path, and so are tested without ink. In the latter case nozzles are tested after integration with the ink path, and so are tested with ink. Segment-wise characterization gives a higher yield, but at a higher testing cost. It is therefore only preferable to printhead-wise characterization when defect densities are still high.

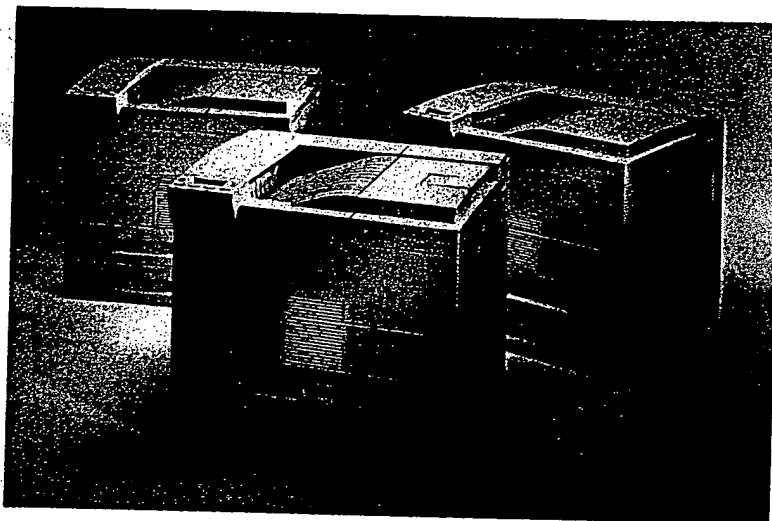
A characterization vector indicates, via one bit per nozzle pair, which nozzle of the pair is to be used. A 12" printhead characterization vector requires 9600 bytes to represent.

Once determined, the characterization vector associated with a redundant printhead is stored in the manufacturing database, indexed by the printhead's serial number, recorded as a barcode on its cartridge. When the printhead cartridge is finally inserted into a printer during manufacture, the characterization vector is retrieved using the barcode, and is written to the flash memory of the printer's embedded printer controller.

If the printhead cartridge is replaced in the field, then a new characterization vector is downloaded remotely from the manufacturing database to the printer controller via its network interface, using the new printhead cartridge's barcode.

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- Flexible, customizable paper handling increases productivity while reducing trips to the printer
- Technologies, software and operations common to HP LaserJet 4000, 5000 and 8000 Series printers

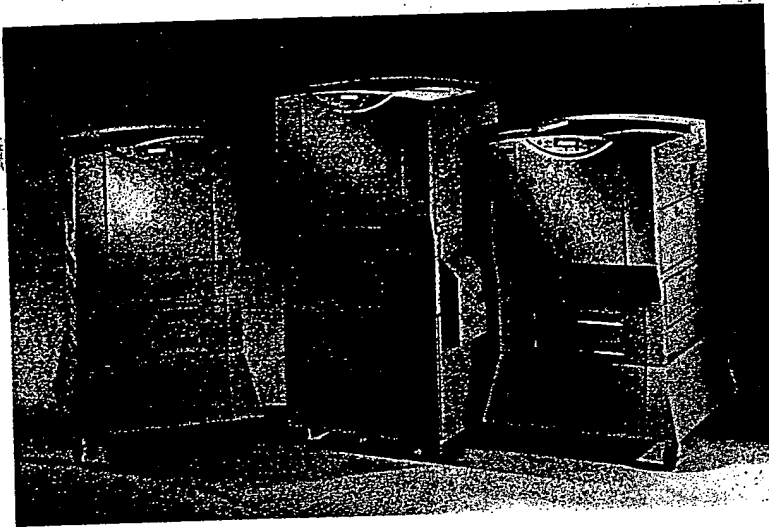
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Color LaserJet 8500 Series

Printers



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- 600-dpi resolution with HP Image Resolution Enhancement technology (HP ImageREt 2400)
- Automatic color matching with sRGB and HP ColorSmart II
- Supports 16- to 58-pound bond paper weights
- Input capacity of up to 3,100 pages through four different input sources (DN model)
- Automatic Color Calibration adjusts the density of each color to give you a greater degree of color consistency from print to print
- Fast multiple prints with dynamic RIP-once technology from a 2.1-GB hard drive

Easy to support and manage.

- Easy remote installation, configuration and management with HP Web JetAdmin
- Optimized for Microsoft® Windows NT® and NT Client environments
- Unique technologies reduce network traffic
- Less frequent supply restocking with high-capacity color consumables
- Backed by HP Customer Care

Industry-leading cost of ownership.

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- Low cost per page
- Optional auto-duplex unit lets you print on both sides of a page automatically
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HP Color LaserJet 4500 Series Printers



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- Lower overall maintenance costs
- Low energy consumption
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